SHALLOW WATER FACIES AND ENVIRONMENTS IN THE ORDOVICIAN OF THE GIRVAN DISTRICT, STRATHCLYDE.

by

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Submitted for the degree of Doctor of Philosophy
in the Faculty of Science, University of Edinburgh

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This is to certify that the work submitted for the degree of Doctor of Philosophy under the title "Shallow water facies and environments in the Ordovician of the Girvan district, Strathclyde." is the result of an original investigation. All authors and works quoted have been fully acknowledged. No part of the work has been accepted in full or part for any degree.

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ABSTRACT OF THESIS (Regulation 6.9)

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Title of Thesis Shallow water facies and environments in the Ordovician of the Girvan district, Strathclyde.

The sediments of the Barr Group (Middle Ordovician, Llanvirn-Caradoc) are described and interpreted within a revised stratigraphic framework. Three Formations, the Kirkland, Stinchar Limestone and Benan are recognised along with their constituent members, on the basis of their environmental significance.

The Kirkland Formation, the lowest in the Barr Group sequence, is inferred to overlie the Middle Arenig ophiolitic terrain of the Ballantrae Igneous Complex, which was emplaced on the northern, Laurentian, margin of Iapetus. Stratification sequences, primary sedimentary structures, fabrics and, where present, faunas, indicate that deposition of the gravel, sand and associated limestone facies that together constitute the Formation took place within a fan-delta setting. Synsedimentary faulting is proposed as the major control over facies development and distribution. Grain size decreases upwards throughout the Formation, documenting gradual transgression and abandonment of the fan delta, with associated establishment of shallow-marine conditions in the Benan Burn Sandstone Formation.

Continued reduction in clastic input resulted in the gradual establishment of a sedimentary regime dominated by deposition of the carbonates of the Stinchar Limestone Formation. Within this unit a variety of facies, shallow-subtidal (Stinchar Valley Member), ?tidal channel (Dupin sequences), oolite shoal and lagoonal (Tormitchell Member), and base of submarine slope (Brochloch Member), are recognised. The cyanophyte alga Girvanella occurs throughout the Formation, displaying a variety of growth forms, these are described and their environmental significance discussed. In addition, a model is proposed for the development of bedding types common in the Stinchar Valley Member, relating the formation of bioturbated planar and undulose bedded limestones, nodular limestones and hardground horizons to variations in sedimentation rates and intensity of bioturbation.

Carbonate deposition was brought to an abrupt halt by a period of rapid local subsidence combined with the effects of the Nemagraptus gracilis zone eustatic

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transgression. These factors resulted in a change from shallow marine to deeper shelf conditions in the Stinchar Valley area. Lowermost horizons of the succeeding Benan Formation, (Conglomerate Member) consists of resedimented gravels interpreted as having been deposited as large scale lobes in the submarine 'toe' of a fan-delta. The laterally equivalent Mudstone Member (formerly 'superstes' mudstones) deposited in the interlobe areas, were eventually transgressed by the resedimented gravels as a result of fan-delta progradation. Higher horizons of the Conglomerate Member possess primary fabrics indicative of deposition in a braided-fluvial environment. This and the presence of shallow-marine, stromatolitic, limestone horizons at higher levels within the Formation firmly attests to the progradation of the inferred fan-delta complex.

The Tappins Group sediments, outcropping between the Stinchar and Glen App faults, are described within a revised stratigraphic framework. Certain units within the Group are correlated with horizons of the Barr Group, demonstrating the continuity of depositional systems across the Stinchar fault. Deposition of Tappins Group sediments took place, however, in deeper water than the Barr Group. The various facies present are taken to indicate deposition within trench, trench slope and outer shelf environments.

Facies types, distribution and development indicate deposition on a narrow, micro-tidal, shelf. Observations made on facies development along both ancient and present day continental margins indicate that oblique-slip motion, probably sinistral in sense, along the northern, subducting, margin of Iapetus provided the major control over Middle Ordovician sedimentation in the Girvan area.

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CHAPTER 1

INTRODUCTION

1.1 Scope and purpose of project

The initial aim of this study was to interpret the depositional environments of the Stinchar and Craighead Limestone (Middle Ordovician) of the Girvan region, Strathclyde. As work progressed it became apparent that there were serious failings in existing interpretations of the Barr Group, of which the Stinchar Limestone is a part. These problems centered around the reconciliation of the received, deep water, slide deposit interpretation of the Benan and Kirkland Conglomerates, that occur above and below the limestone, with the obviously shallow water nature of this unit. Previous attempts to account for this apparent disparity were felt to be self contradictory, for reasons outlined later in this thesis. At the same time it was realised that the Craighead Limestone exposures were too highly tectonised to allow the type of study initially intended. For these reasons it was felt that the project should be directed towards gaining an understanding of the depositional environments of the Barr Group, with the intentions of resolving the above mentioned problem, providing an account of the sedimentary development of this particular portion of the northern margin of Iapetus. During the final year of study a brief investigation of the Tappins Group sediments was carried out with the intention of determining whether they actually were trench deposits, as suggested by previous authors, or whether they might in fact be laterally equivalent to the Barr Group sediments, though deposited in deeper water.

1.1.1 Layout of thesis

The remainder of this introductory chapter is intended to give the reader an insight to the geology of the area studied, to provide a background to the somewhat broader aspects of Caledonian/ Appalachian geology and Ordovician palaeogeography and changes in sea level in the context of the present study. The stratigraphic framework within which the Barr Group sediments are interpreted is outlined in Chapter 2. The Kirkland Formation, the lowest in the Barr Group, is described and interpreted in Chapter 3 and a model for the deposition of the unit proposed. Chapter 4 deals with the Stinchar Limestone Formation, a complex unit consisting of a wide variety of carbonate lithologies and facies. In addition a model for the development of various types of bedding common in limestones is outlined. The highest unit in the Barr Group, the Benan Formation, interpreted in Chapter 5, is of critical importance in interpreting the conglomerates that dominate the lower part of the Ordovician sequence in the Girvan region. The results of a study of the Tappins Group sediments that occupy the area between the Stinchar and Glen App faults are presented in Chapter 6. Chapter 7 summarises the findings discussed in previous chapters and on the basis of these, documents the Middle Ordovician depositional history of part of the northern margin of Iapetus.

1.1.2 Location

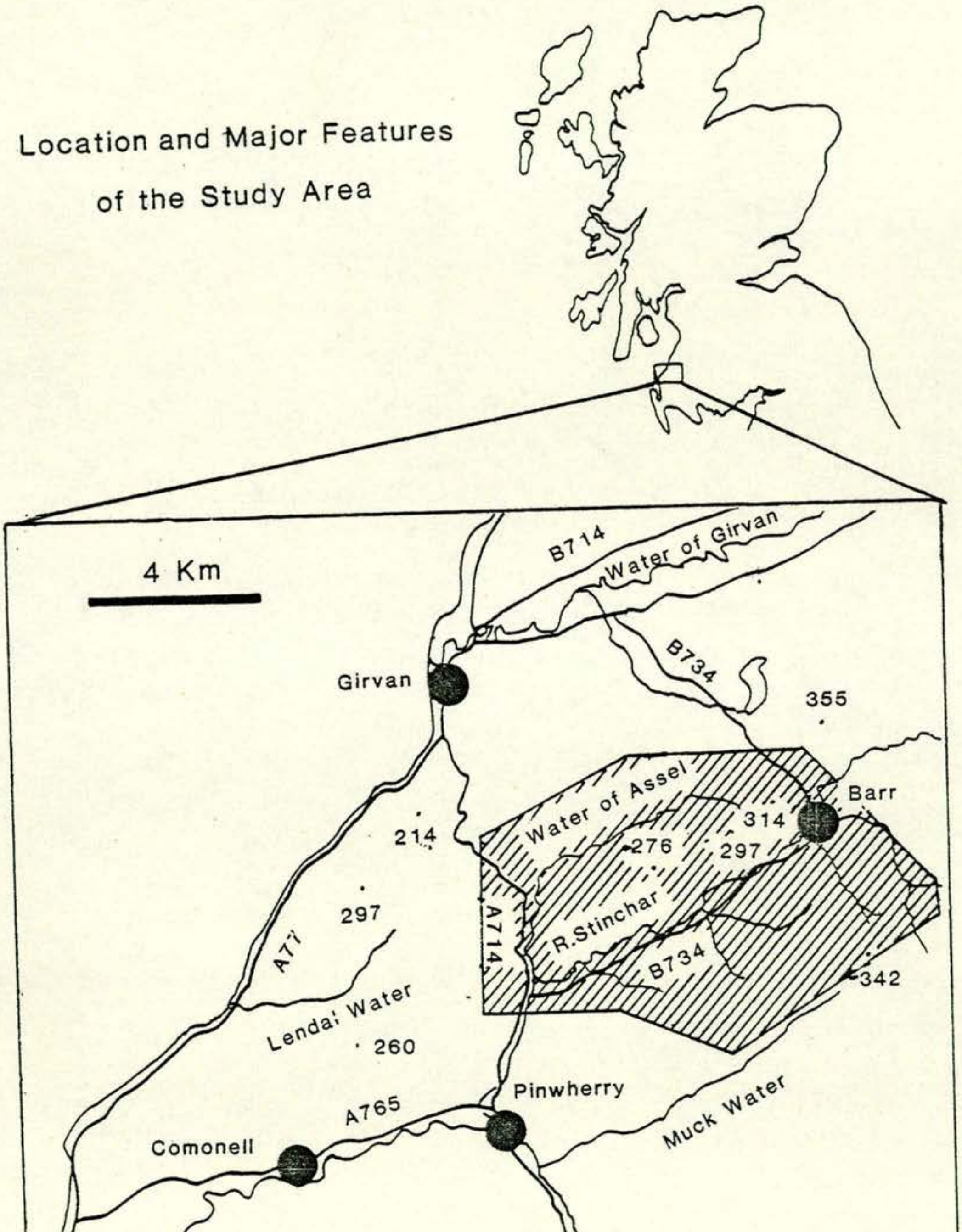
The Girvan region lies on the south-west coast of Scotland, 80Km S.S.W. of Glasgow and 40Km N.N.E. of Stranraer, see Figure 1:1. The area studied lies to the S.E. of the town of Girvan, and is roughly bounded by the roads A714 and B734 to the west and east respectively, Fig. 1:1. The valley of the Water of Assel marks the northern limit of the study area, whilst to the south an approximate boundary is provided by the Southern Uplands Fault.

1.1.3 Techniques

Field data was collected primarily in the form of detailed section logs with careful descriptions of the logged units. No mapping of the area was undertaken as it was felt unlikely that in the time available it would be possible to improve on the map published by Williams (1962). Complementary laboratory work involved thin section petrography, the examination of acetate peels of stained and polished surfaces and detailed study of core sections recovered from the I.G.S. Benan Burn Borehole. Insoluble residues and microfossils, particularly conodonts, extracted from the Stinchar Limestone Formation, were examined using a scanning electron microscope.

Figure 1.1

Location and Major Features of the Study Area



1.2 Brief outline of Geology

The Girvan region lies in the Midland Valley of Scotland immediately to the north of the low-grade metamorphic, paratectonic greywacke - turbidite belt of the Southern Uplands. It is one of several Lower Palaeozoic inliers (Fig. 1:2) in the Upper Palaeozoic belt of the Midland Valley which is bounded to the North, across the Highland Boundary Fault by the various Precambrian and Cambro-Ordovician units that form the orthotectonic higher grade metamorphic Caledonides. The area studied comprises an assemblage of Middle Ordovician (Llanvirn-Llandeilo) conglomerates, limestones, turbiditic and non-turbiditic sandstones.

Two units, the Benan and Kirkland Conglomerates, derived from the local basement (the Ballantrae Igneous Complex) dominate the Barr Group sequence, which is exposed to the north of the SW-NE trending Stinchar Fault (Fig. 1:3). The location of this important fault zone is marked by the course of the eponymous R. Stinchar. In the stratigraphic interval between these two units a relatively thick sequence of sandstones, fine grained limestones and silty mudstones denotes a pause in the deposition of coarse grained material.

Barr Group conglomerates, limestones and sandstones are exposed as far north as the Water of Assel, whose course again marks the line of a S.E.-N.E. trending fault. Between this, the Assel fault, and the Stinchar fault to the south, the Barr Group sediments are folded into a broad synclinal structure, the Benan syncline.

From the Stinchar Valley southwards to the Glen App fault a varied set of greywacke turbidites, collectively termed the Tappins Group (Peach and Horne, 1899) outcrop in the various N. flowing tributaries of the R. Stinchar. Certain of the sediments outcropping in this tract of land have been correlated with horizons in the Barr Group, although the general absence of fauna creates serious stratigraphic problems. In addition to the marked facies change, from shallow water sediments to turbidites, across the Stinchar Fault, there is also a striking change in structural style. To the North the Barr Group sediments are relatively openly folded, with high dips present only at a few outcrops. Southwards in the Tappins

Figure 1.2

Simplified geological map of Scotland.

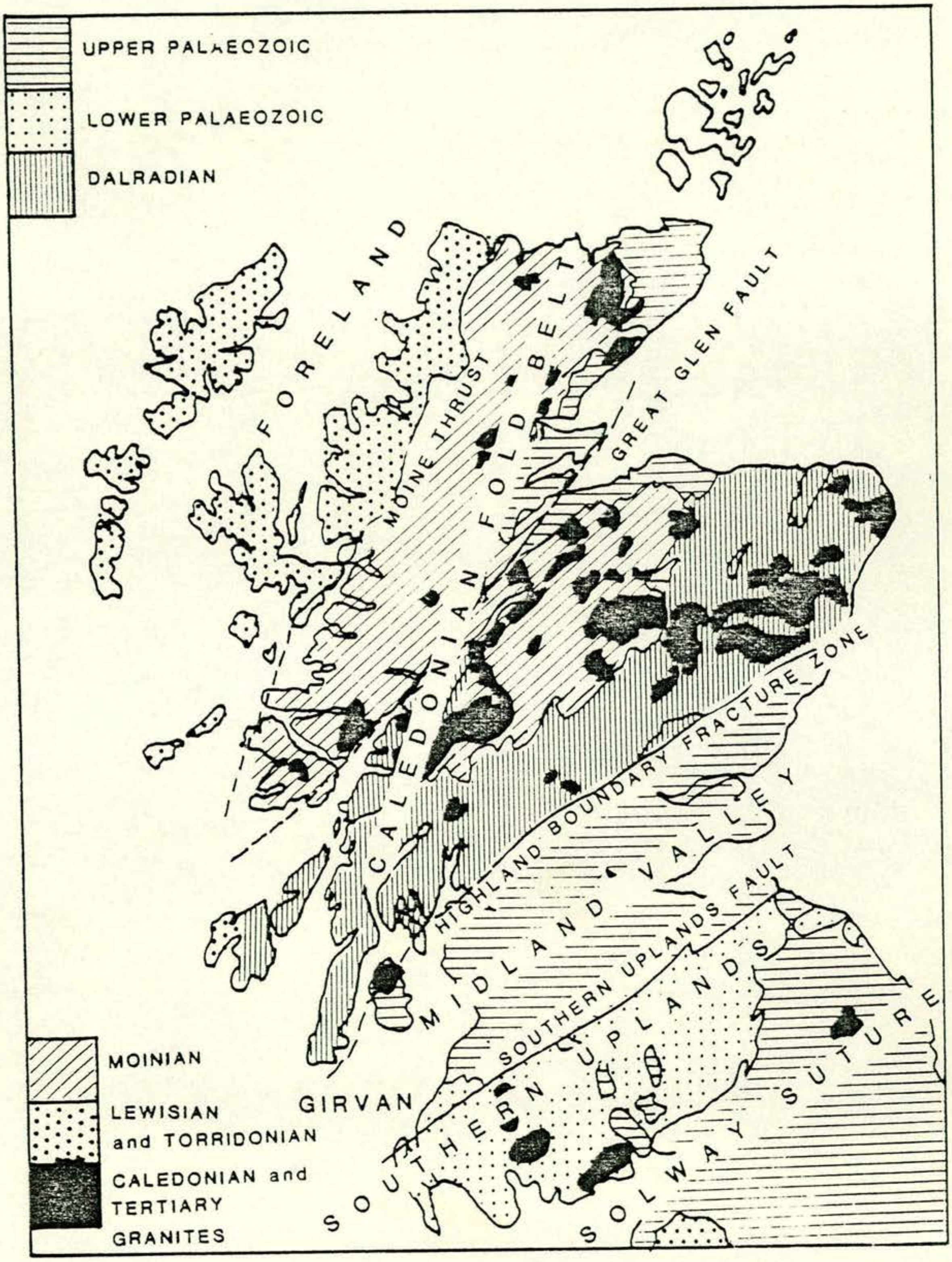
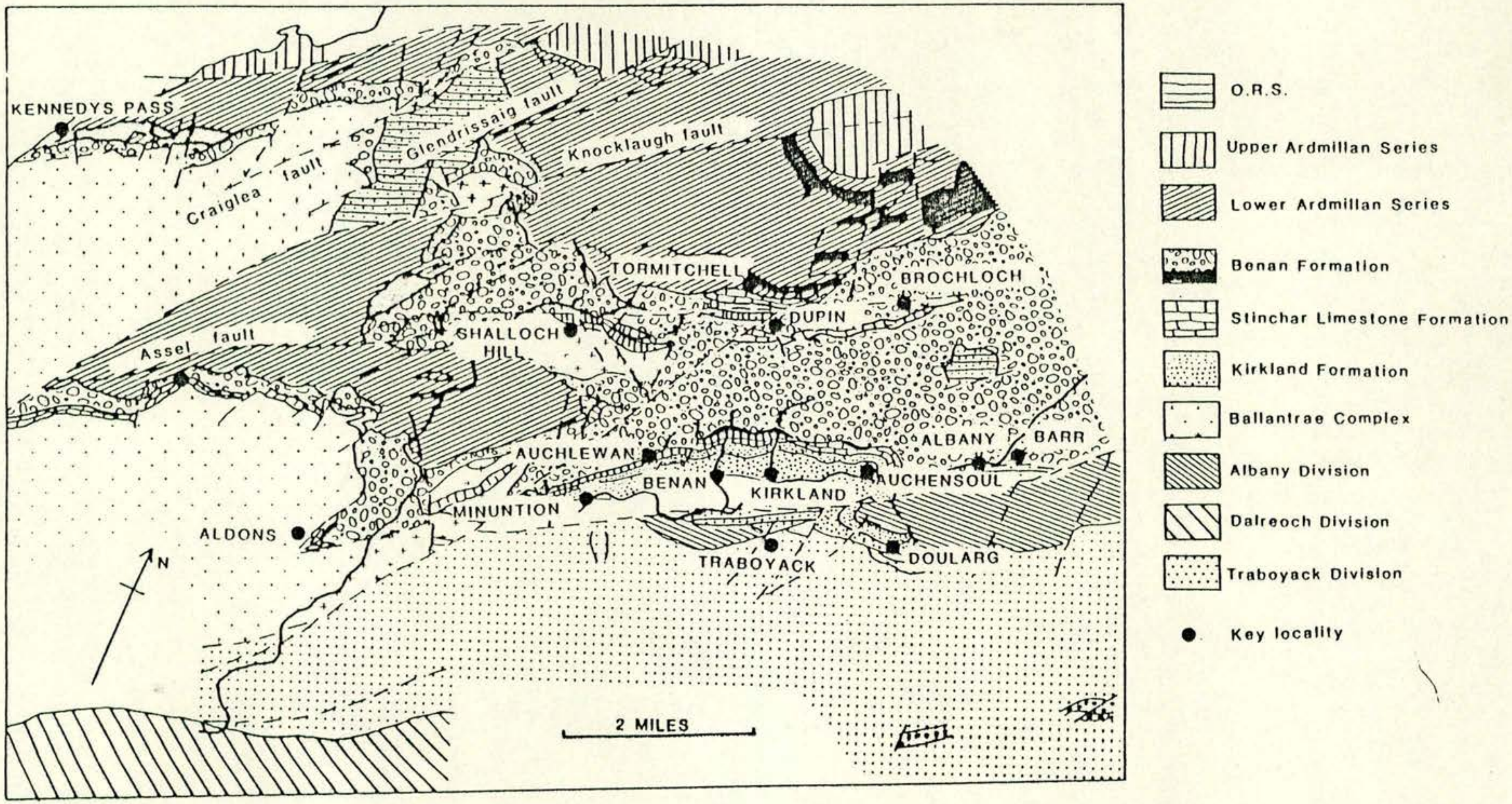


Figure 1.3

SIMPLIFIED GEOLOGICAL MAP OF THE GIRVAN AREA



Group, bedding is usually near vertical, and over-turned strata are moderately common. Williams (1959, Fig. 4) deduced the presence of a series of tight, upright folds in Tappins Group exposures along the Water of Gregg. The current paucity of exposure in this area precludes confirmation of this complex situation, although similar structures can be recognized in Traboyack Burn, 5Km to the west. In addition, the Tappins Group rocks are cut by a number of relatively large scale shear and crush zones. These cannot in general be traced laterally and the extent of any movements cannot be determined.

1.2.1 History of Research

During the middle of the last century many of the most notable geologists of the day, Sedgwick, Murchison and Geikie addressed themselves to unravelling the stratigraphy of the Lower Palaeozoic sediments of the Girvan region. Equally emminent palaeontologists, McCoy, Salter, Davidson and Wyville-Thompson, studied the diverse fossil faunas contained within these rocks. On the basis of the evidence thus provided, these workers assigned a Llandeilo age to the Stinchar Limestone and recognised faunas of Caradoc and Llandovery age within the succeeding sequence.

The two most notable works on the Girvan area did not appear until the final quarter of the last century. In 1882 Charles Lapworth published what is by any standards a brilliantly lucid account of the Girvan succession. In this paper Lapworth presented a clear statement of the stratigraphy of the area, resolving what had previously been a "vexed question" although his scheme has been modified by later authors. At approximately the same time Nicholson and Etheridge were documenting a vast collection of fossils made by Mrs R. Gray, published as a monograph in three parts (1878, 1879, 1880) and providing a comprehensive although by no means complete description of the faunas.

Peach and Horne, having mapped the whole of the Southern Uplands area for the Geological Survey devoted a major part of their memoir in 1899 to the Lower Palaeozoic sediments of the Girvan area. Certain stratigraphic errors made by Lapworth were corrected by these authors, the Stinchar Limestone being recognized as a single unit, rather than a series of separate horizons as proposed by Lapworth, but in general the opinions of this author were upheld. With regard to the structure of the area Peach and Horne, apparently obsessed with isoclinal folds, despite a singular lack of evidence considered that the remains of no less than six such anticlines, paired with five synclines, were recognizable on the north slopes of Benan Hill and in the Assel Valley (Peach and Horne, 1899, Fig. 111).

Considering the comprehensive nature of the publications and the status of their authors it is hardly surprising that a period of relative quiescence followed. F.R.C. Reed published a long series of papers (1917, 1935, 1940, 1944, 1945) describing new species of brachiopods from the area. Fresh discoveries of new trilobite occurrences were similarly treated by Begg (1939, 1946, 1950[A,B]).

Henderson (1935) recognized the presence of hitherto undetected unconformities within the Ordovician sequence. He used this discovery and the presence of slumped horizons in the Ardwell Group to infer earthquake related synsedimentary disturbance of these sediments during the Ordovician period.

As the result of a lengthy period of research two major contributions were published by Alwyn Williams, in 1959 and 1962. The first of these addressed the problems posed by the complex structure of the Girvan area, and superseded the somewhat unrealistic interpretation provided by Peach and Horne (1899). This structural interpretation was made possible by an appreciation of the biostratigraphy of the area brought about by the recognition of a set of brachiopod faunules each indicative of a particular stratigraphic interval. Taxonomic descriptions of these brachiopod faunas were published in Williams" 1962 memoir "The Barr and Lower Ardmillan Series", along with a description and basic interpretation of the sediments in which these faunas occurred. In his final synthesis, Williams proposed that the distribution of Ordovician sediments in the Girvan succession, was controlled by syn-sedimentary movements along a series of S.W.-N.E. trending faults, see Fig. 1:3. It was within the framework provided by this model that the present study was undertaken, and it should be stated at this point that the author concurs fully with this broad conclusion. In sedimentological terms, however, Williams' work reflects the relatively simplistic, conventionally stratigraphic, approach that would seem to have been in general usage at the time when interpreting sedimentary sequences. This lack of appreciation of subtle variations in facies and their significance led Williams to conclusions now felt to be invalid for reasons outlined at the appropriate places in this thesis.

With the advent of plate tectonic theory the Lower Palaeozoic sediments of the Southern Uplands have been interpreted as having been deposited along the northern margin of a former ocean that separated Scotland from the English-Welsh areas (Wilson, 1966, Dewey, 1969). The presence of this ocean, later named Iapetus by Harland and Gayer (1973) was inferred from various lines of evidence as outlined in Sections 1.3.1 to 1.3.3.

1.3 Evidence for the Iapetus Ocean

1.3.1 Ordovician Palaeobiogeography

Long before the use of fossil invertebrate faunas as an aid to plate reconstructions the close affinity of the Girvan brachiopod faunas with those found in North America was realized by Lapworth (1888). More recently, the recognition of distinctive assemblages of fossils, restricted in their palaeogeographic distribution, has led to the concept of faunal provinces. During the Ordovician period, three such provinces have been recognized throughout Europe, North America and the British Isles. The North American faunal province exists in part in the Scottish and Northern Irish areas during the Lower and Lower Middle Orodovician (Williams, 1969, 1973, Whittington and Hughes, 1973, Cocks and Fortey, 1982). Equally distinctive and separate are fossil assemblages that denote faunal provinces typical of the Anglo-Welsh and Baltic areas. During the Ordovician period the discrete nature of the faunas in areas formerly typified by one or other of the above faunal provinces becomes less apparent and during the Silurian there is a distinctly cosmopolitan aspect to the fossil assemblages. Various authors have suggested that this marked change in invertebrate population composition is related to the closure of the Iapetus Ocean (Williams, 1973, Whittington and Hughes, 1973, Dean, 1976, McKerrow and Cocks, 1976, Cocks and Fortey, 1982) which during the Arenig may have separated the North American from the Anglo-Welsh/Baltic faunal provinces by as much as 60^{0} of latitude (Cocks and Fortey, 1982).

1.3.2 Palaeomagnetism

The palaeolatidinal separation of continents at a given time may be determined by differences in the orientation of the natural remnant magnetic field in susceptible rocks of the same ages. Reconstructions of plate distributions during geological time have been published by various authors (Smith et al., 1975, Morel and Irving, 1978, Scotese et al., 1979). In the maps constructed by these authors the Scottish and N. Irish areas are considered as part of the Laurentian continent, separated from Gondwanaland, of which the Anglo-Welsh area is a part, by the same latitudinal extent, 60^{o}, as suggested by Cocks and Fortey (1982) on faunal evidence, see Fig. 4:8.

The degree of longitudinal separation of continental areas, or the extent of any rotation, is more difficult to determine. Recently, however, Scotese et al (1979) and Scotese and Van der Voo (1981) have suggested major lateral separation of the two areas, until juxtaposed by extensive strike-slip motion, during the Upper Palaeozoic.

During the Middle Ordovician the Scottish area is thought by all these authors to have occupied a position immediately to the South of the equator, Fig. 1:4.

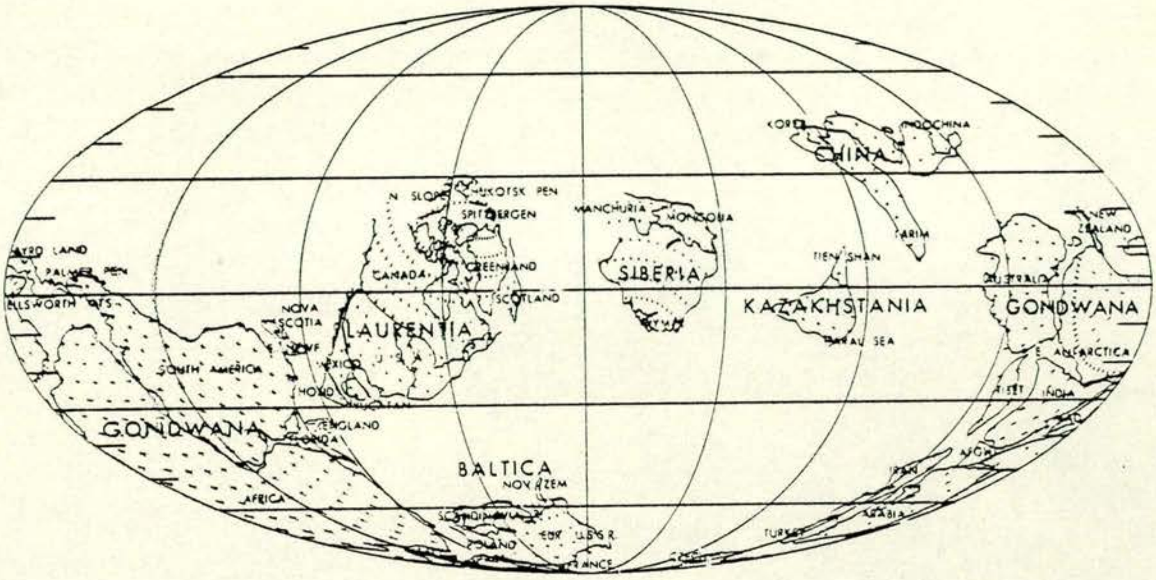
1.3.3 The Ballantrae Igneous Complex - an Early Ordovician Ophiolite

Ophiolites, segments of oceanic crust generated within ocean basins and subsequently tectonically emplaced within an orogenic belt, are generally considered to denote the presence of a former ocean basin, and by implication their site of emplacement is taken to be close to a former continental margin (Dewey and Bird, 1971, Church, 1972, Conference participants, 1972).

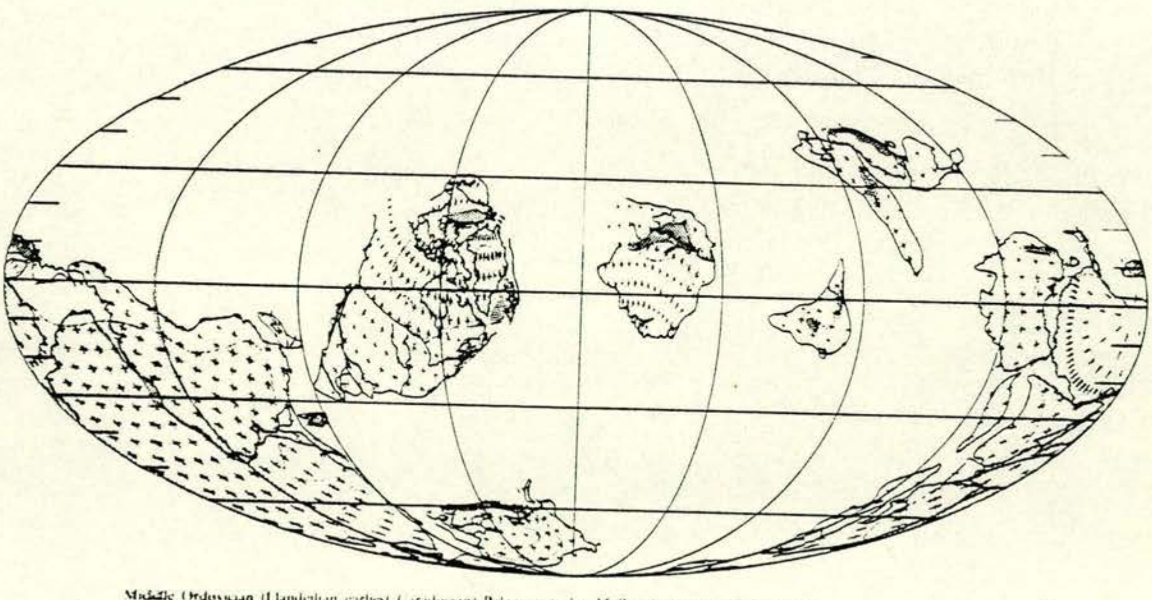
The Ballantrae Igneous Complex, which forms the basement upon which the Barr Group and younger Ordovician sediments were deposited, has been interpreted as an ophiolite emplaced on the northern continental margin of Iapetus during the middle to later Arenig (Dewey, 1971, Church and Gayer, 1973, Lewis, 1975, Jones, 1978, Bluck, 1978, Bluck et al., 1980). The lithological association typical of ophiolites, basaltic lavas with a veneer of chert and/or black shales, gabbros and serpentinites, are all present (Dewey, 1971, Church and Gayer, 1973) though a true sheeted dyke complex is not clearly

Figure 1.4

Ordovician Palaeogeography.



Middle Ordovician (Llandeilian earliest Caradocian) Locality Map. Mollweide projection "front view" as on figure 1



Middle Ordovician (Llandeilian earliest Caradocian) Paleogeography. Mollweide projection "front view". Deep oceans, unshaded; shallow seas, light shading; low land, intermediate shading; mountains, dense shading

from Scotese et al 1979.

represented. Whether this fragment of oceanic crust was obducted in the sense proposed by Dewey and Bird (1971) for Appalachian ophiolites in Newfoundland, or whether some other process was involved is not clear. The author feels that the marginal basin/island arc origin proposed by Bluck et al. (1980) is unrealistic and agrees with critical objections to this model voiced by Barret et al. (1982).

1.3.4 Caledonian Plate Tectonic models

Since the revolutionary model proposed by Dewey (1969 and 1971) in which the evolution of the Scottish Caledonides was related to the iniation of a North-West dipping subduction zone along the line of the Southern Uplands fault and the activity of a destructive margin along this line during the Lower Palaeozoic, there has been a profusion of similar models each thought by the authors to be more realistic than the previous opinion (Fitton and Hughes, 1970, Gunn, 1973, Mitchell and McKerrow, 1975, Lambert and McKerrow, 1976, Phillips et al., 1976).

It is beyond the scope of the current work to engage in a review of these and for a full assessment of the applicability of each model the reader is referred to the excellent critique of Jones (1978).

Recently, however, a new dimension has been introduced into Appalachian/Caledonide geology. The importance of strike-slip or oblique-slip motions at plate margins as an alternative, to the subduction zone model for orogenic belts, has been documented by Mitchell and Reading (1978). Since then fresh palaeo-magnetic evidence has led to various authors (Bluck, 1980, Henderson and Robertson, 1982, Curray et al., 1982, Yardley et al., 1982) to invoke strike-slip motions as an explanation for a variety of features within the Caledonides. On a more, and perhaps more realistic, scale Dewey (1982) has proposed an overall oblique-slip model for the Appalachian/Caledonian orogen. Within this regime Dewey proposes that first the Highland Boundary and then the Southern Uplands fault were the sites of subduction zones. That which lay along the Highland Boundary fault was active until the Arenig, when the 'docking' of an oceanic plateau resulted both in the Grampian orogeny, and the establishment of a second northerly dipping subduction zone, to the south of this 'docked' crustal unit, along the Southern Uplands Fault. During the remainder of the Lower Palaeozoic, oblique subduction is inferred to have taken place along this line, until continental collision and suturing took place in the Lower Devonian. There still remains a problem in resolving the type of model proposed by Dewey (1982) with certain palaeomagnetic results (Scotese et al., 1979, Scotese and Van der Voo, 1981, Kent and Opdike, 1979) where differing senses and timing of motion are proposed.

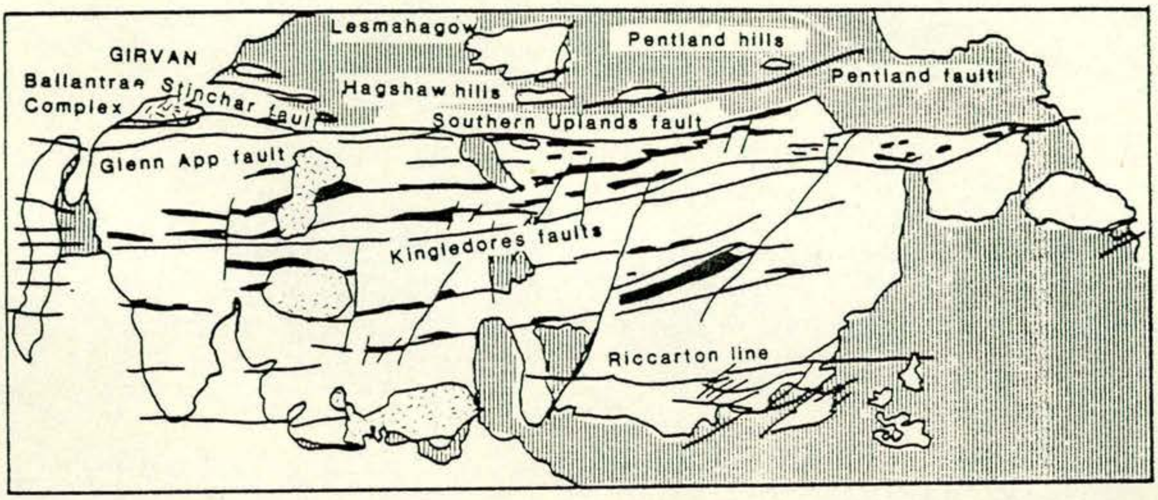
Whilst the above is intended as a broad introduction to Caledonide geology, certain points detailed below are felt to be of potential significance to the present work.

Following the opinion of Mitchell and McKerrow (1975) the Southern Uplands are now generally believed to represent an accretionary prism (McKerrow et al., 1977, Legget et al., 1979, 1982). Comparable present day structures are found at active margins where portions of a thick trench sequence are successively offscraped, leading to a thick deformed, sediment pile (Karig and Sharman, 1975), see Fig. 1:5.

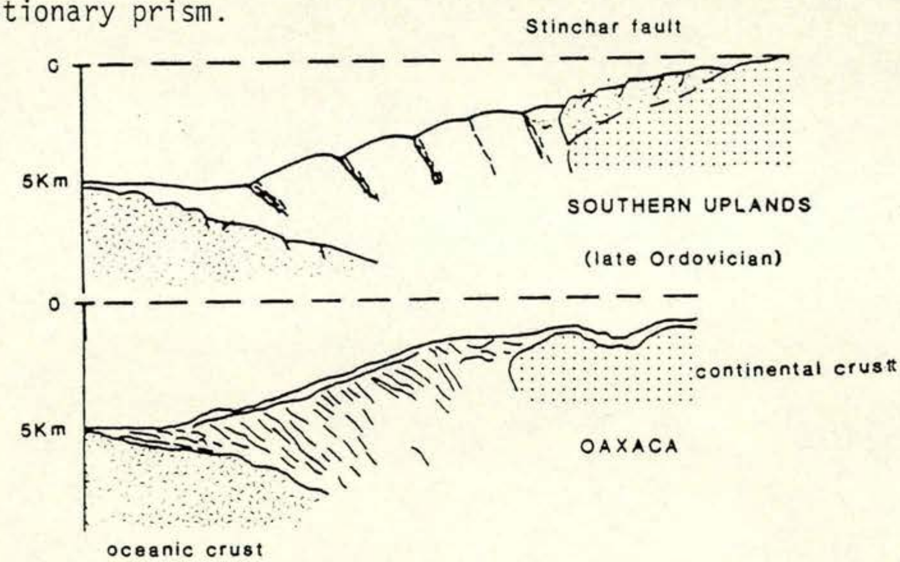
Various authors (Mitchell and McKerrow, 1975, McKerrow et al., 1977, Legget, 1980, Legget et al., 1979, 1982, Longman et al., 1979, Van Breeman and Bluck, 1981) have interpreted the Midland Valley of Scotland as the site of a volcanic arc. This presumed arc was inferred on the basis of the presence of andestic clasts in Caradocian sediments of the Rhinns of Galloway (Kelling, 1961) and of granitic clasts dated at 470my in the Benan Conglomerate of Girvan region (Longman et al., 1979), and also as a result of the need to find an arc to the north of the S. Uplands to justify the existence of a subduction zone. At the same time, however, the aforementioned authors choose to site the Caradocian subduction zone to which this arc, is related, along the Southern Uplands Fault. Present day arc.trench gaps are a minimum of 55Km and generally around 100Km (Dickinson, 1973, Dickinson and Seely, 1979). If the assumption that the Southern Uplands fault represents more or less, the site of an Ordovician subduction zone, then the associated arc cannot be further south than the Highland Boundary Fault (Yardley et al., 1982). These authors further suggest that the Southern Highlands are the most reasonable source area for

Aspects of the Southern Uplands Accretionary Prism.
(after Legget)

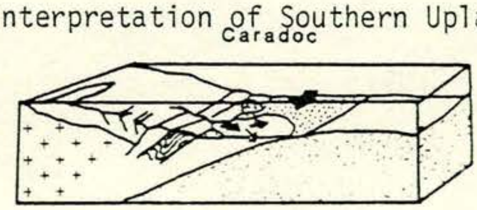
Major Structural features of the Southern Uplands.



Comparison between the Southern Uplands and a present day accretionary prism.



Diagrammatic interpretation of Southern Uplands sedimentation during Caradocian period.



continental crust

subducting plate

Developing prism with axially and laterally derived turbidites detritus in Southern Uplands sediments formerly thought to indicate the presence of a Midland Valley arc terrain, thus returning to the original opinion of Dewey (1971, Fig. 5).

In view of the above points it is worth noting the results of Upton et al., (1976) and Graham and Upton (1978) who record xenoliths of granulitic gneiss from a Carboniferous vent at Partan Craig, a localith within the Midland Valley. These nodules have yielded a Sm/Nd isotopic age of 1180$\pm$ 55my (Van Breeman and Hawkesworth, 1980). Dickin et al. (1981) using evidence obtained from geochemical studies of the Tertiary igneous rocks of Arran, propose that a late Pre-Cambrian orthogneiss complex having an apparent age of 770$\pm$ 180my (Pb/Pb) lies below Arran. Work carried out in part by the present author on clasts from the Kirkland Conglomerate may also indicate the presence of a Pre-Cambrian basement to the Midland Valley, see Chapter 3.

If the above conclusions and those reached in (b) are correct then the Grampian Orogeny (Lambert and McKerrow, 1976) the climax of Dalradian metamorphism at around 500Ma (Dewey and Pankhurst, 1970, Lambert and McKerrow, 1976, Yardley et al., 1982) may be related to the collision of a micro-continent - represented by the late Pre-Cambrian area of Southern Scotland with the main Laurentian continent to the N., perhaps in the manner suggested by Henderson and Robertson (1982) and Dewey (1982), an opinion strongly favoured by the present writer.

Finally,there is the possibility, discussed in section 7.2 that oblique slip motion may have occurred along an Ordovician subduction zone located in Southern Scotland and now equated with the Southern Uplands Fault. The importance of this concept lies in the profound effect that motions of this type may potentially have, in determining the distribution and type of facies developed along such a margin (Mitchell and Reading, 1978, Reading, 1980).

Along strike-slip margins two types of tectonic activity may take place, transpression, leading to folding, thrusting and vertical uplift on land, and perhaps also of adjacent sedimentary basins, and transtension, leading to basin subsidence along closely spaced normal faults (Reading, 1978). Basins developed within a transpressional regime are thus more likely to develop within subaerial environments and have a low preservation potential. On the other hand, those forming within a transtensional regime are likely to be thick accumulations, provided they form on land or at a continental margin. Strike-slip regimes are further characterized by pronounced, although often localized, vertical dip-slip faulting. This combined with the horizontal movements, provides an effective mechanism, within a continental margin setting, of juxtaposing a source area undergoing uplift against a marine basin capable of receiving large volumes of detritus.

1.4 Ordovician palaeoclimates and sea levels

Changes in relative sea level are capable of having profound effects on the pattern of sedimentation in a given area, as demonstrated by Vail et al. (1977). Sea level changes may either be local, caused by localized tectonic activity, or eustatic (world wide). In the latter case the phenomena may be manifested by synchronous world-wide unconformities (Rona, 1973). Such changes in sea level may also have significant effects on the nature and distribution of shallow-marine invertebrate faunas (McKerrow, 1979). The recognition of such events in the geological record is of obvious importance in interpreting ancient sequences, and in identifying localized periods of uplift or subsidence.

During the Ordovician period several major changes in sea level can be recognized. The earliest of these events occurred during the Arenig (Spjeldnaes, 1961, Bigarella,1964, Shaw and Fortey, 1977, Cocks and Fortey, 1982), these authors recognizing a major regression on the basis of faunal evidence. Stratigraphic support for this opinion can be found throughout the Appalachian area. Cummings (1968) describes a mineralized regional disconformity of 290Km in lateral extent occurring between the St. George formation (Cambro-Ordovician) and the Table Head formation (Middle Ordovician) of Newfoundland. In Tennessee, 2,500Km to the south-west, the surface of the Lower Ordovician Mascot Dolomite is eroded into a spectacular palaeo-Karst with a fossil relief of up to 65m, and is overlain by Middle Ordovician sediments (Rodgers and Kent, 1948, Bridge, 1955). Similar disconformities are recorded from Alabama (Butts, 1926), Virginia (Butts, 1940, Cooper and Prouty, 1943), New England and

Quebec (Hall, 1969). In the case documented by Hall, the Cambrian(?) sediments were not only uplifted by also deformed prior to the deposition of the overlying Middle Ordovician sediments. Within the Scottish Caledonides, this intense pre-Taconic deformation event may be correlated with the initial Dalradian deformation (Hall, op cit., p.476) and perhaps with the Grampian Orogeny (Lambert and McKerrow, 1976). Furthermore, this event is approximately synchronous with the exposure of the Ballantrae Igneous Complex (see section 1.3.3).

Following this regression, which if not eustatic must represent a major tectonic event, a gradual transgression occurred throughout the Llanvirn. In the Nemagraptus gracilis zone a rapid increase in water depths, inferred from stratigraphic, faunal and palaeo-oceanigraphic data, took place, and is considered to have been a major eustatic event (Spjeldnaes, 1961, Ross, 1976, McKerrow, 1979, Legget, 1978, Vail et al., 1977). Sea levels remained relatively high until the late Ashgill when eustatic regression associated with a glacial period took place (Berry and Boucot, 1973, Sheehan, 1973, Dennison, 1976, Ross, 1976, Brenchley and Newall, 1980, McKerrow, 1979, Legget, 1978).

CHAPTER 2

BARR GROUP STRATIGRAPHY

2.1 Introduction

The Ordovician of the Girvan area has been the subject of three classic stratigraphical works; Lapworth (1882), Peach and Horne (1899) and Williams (1962). Each of these authors has put forward a somewhat different stratigraphic framework for the Barr Group, as discussed below, a summary of the various schemes is shown in Fig. 2:1.

The sequence proposed by Lapworth has largely been accepted by later authors, though it is now clear that he failed to recognise the age difference between the Stinchar and Craighead Limestones, (Peach and Horne, 1899) and thus assigned the latter to the Barr Series. However he did record the occurrence of the sporadically developed Auchensoul Limestone, (Williams, 1962).

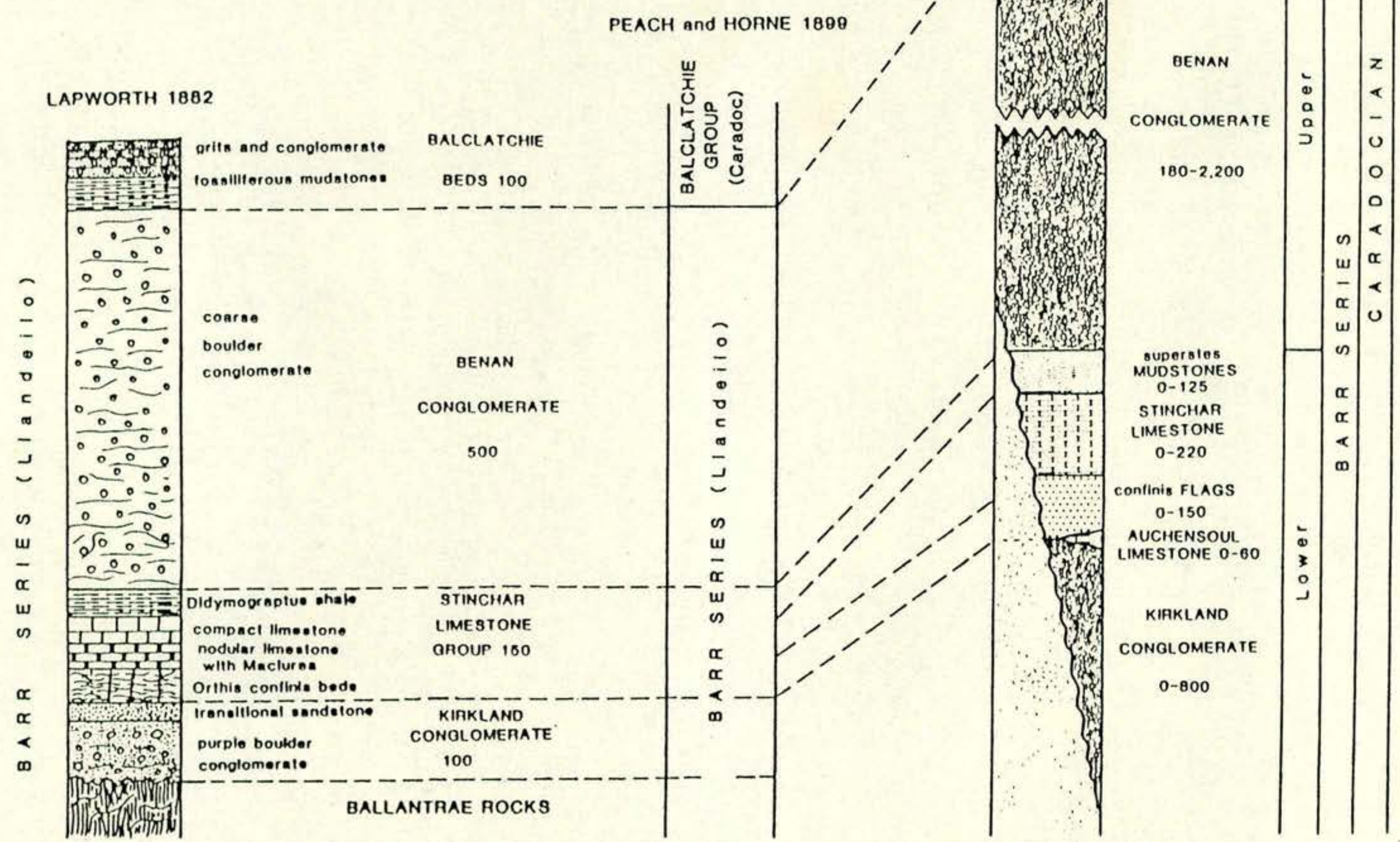
Peach and Horne (1899) retained Lapworth's stratigraphic sequence but placed the upper boundary of the Barr 'Series' at the top of the Benan Conglomerate, feeling this horizon to be a more readily traceable datum than the boundary proposed by Lapworth (1882). They also realised that despite certain similarities in sequence the Craighead Limestone was a separate, younger, stratigraphic unit, distinct from the Stinchar Limestone, and not part of the Barr Group.

Williams (1962) recognised the existence of the Auchensoul Limestone, occurring above the Kirkland Conglomerate. Certain stratigraphic units used by Lapworth (1882) and Peach and Horne (1899) were, however, abolished without explanation. Thus the Kirkland Group, Red and green sandstones of Lapworth (1882), Purple sandstones and grits of Peach and Horne (1899) and the Maclurea beds of these authors, occurring as the lower part of the Stinchar Limestone, were not recognised by Williams as valid divisions.

In addition Williams divided the Barr 'Series' into two, the lower boundary of the upper unit being placed at the base of the Benan conglomerate.

Figure 2.1

PUBLISHED STRATIGRAPHIES OF THE BARR SERIES



2.2 Age of the Barr Group

The timing of the onset of sedimentation over the previously emergent Ballantrae Igneous Complex is clearly of major importance in the context of the regional and local events outlined in Chapter 1.

Lapworth (1882) and Peach and Horne (1899) considered the Barr 'Series' to be of Llandeilo age, in agreement with the opinion of Murchison (1851). Williams (1962) claimed a Caradocian age for the entire Girvan succession, up to the base of the Upper Ardmillan Series. The main reasons given, as later summarised by Ingham (1978, p.166) are as follows. Supposed correlatives of the Nemagraptus gracilis zone which at the time was considered to be the lowest graptolite zone in the Caradoc, were thought to exist in the 'superstes' mudstones. Addison (in Williams et al 1972) subsequently demonstrated that the N. gracilis zone is, for the most part, of Llandeilo age, only a small part of the zone being present in the type Caradoc sections in Shropshire. Thus the basis for Williams (1962) age determinations may no longer be valid, and since the zone fossil N. gracilis is absent from the 'superstes mudstones', there is no proof of a Caradoc age for sediments deposited prior to the mudstones.

Using a conodont zonation developed in Scandinavia and applied to the Appalachian region, Bergstrom (1971) reported the occurrence of the Pygodus anserinus/Pygodus serrus zonal boundary, equated with the Llanvirn/Llandeilo boundary, within the Stinchar Limestone Formation of Benan Burn. A full treatment of the Barr Group conodont faunas has not yet been published, however collections made by the present author confirm Bergstrom's (1971) findings (see Chapter 4).

Insufficient material was collected from localities other than Benan Burn to establish the position of this boundary, and Bergstrom (1981 pers.comm.) reports similar lack of success.

2.3 Correlation of the Barr Group with the North American standard successions

Both Lapworth (1882) and Nicholson and Etheridge (1876) commented on the similarity between the brachiopod faunas from the Girvan area and those from the Appalachian region of the U.S.A.. Williams (1962) correlated brachiopod faunas from the upper part of the Stinchar Limestone Formation at Brochloch with those occurring in the Little Oak and Pratt Ferry Formation of Alabama. More generally he concluded that Stinchar Limestone Formation faunas were indicative of a low Porterfield age according to the American standard sequence defined by Cooper (1956).

Detailed researches in conodont biostratigraphy summarised by Bergstrom (1971) suggest that the Little Oak and Pratt Ferry Formations might more correctly be placed in the Chazy, rather than the Porterfield stage. Bergstrom also confirms the correlation of the Barr Group with the Chazy stage, reporting the same conodont faunas from respective type sections, and noting the particular similarity of Stinchar Limestone Formation faunas to those from the Arline Formation of Tennessee.

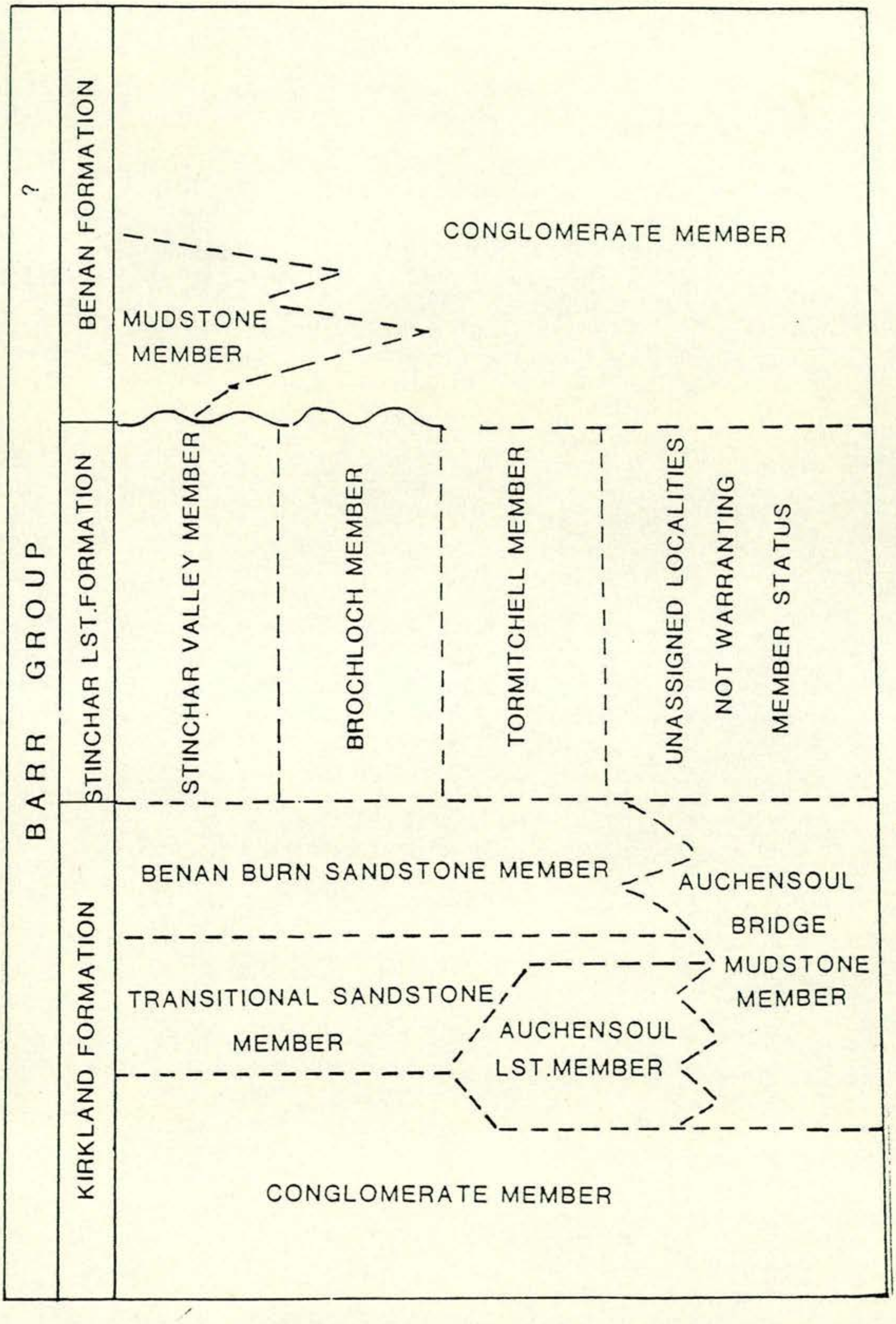
2.4 Stratigraphic revision of the Barr Group

Since the work of Williams (1962) the vastly increased volume of publications dealing with stratigraphic problems has resulted in the need for a standarised framework within which to describe the stratigraphy of a given area. The International Subcommission on Stratigraphic Classification (I.S.S.C.) have published recommendations for correct stratigraphic procedure (Hedberg, 1976) and since Williams monograph predates these much of his terminology does not conform to these guidelines. In addition, Williams's stratigraphic system does not truly reflect relationships within the Barr Group.

All previous stratigraphies of the Girvan area have been lithostratigraphic in nature (Lapworth 1882, Peach and Horne 1899, Williams 1962). It is therefore intended to redefine the Barr Group according to the formal hierarchical classification of lithostratigraphic units outlined by Hedberg (1976, p.32), with type sections nominated for the various subdivisions. (Although publication in thesis form does not formalise a proposed stratigraphic scheme). Figure 2:2 summarises the scheme used in the present work. As far as possible divisions have been made in an attempt to delineate units into environmentally meaningful groups. The scheme outlined here has attempted to redefine the Barr Series in

Figure 2.2

Revised stratigraphy of the Barr Group.



terms of the I.S.S.C. guidlines, whilst as far as possible retaining traditional names.

2.4.1 Barr Group

Whittington (in Williams et al 1972) emended the term Barr Series as Barr Group, but did not provide definitions of either the group as a whole or any of the component formations. The group is bounded by the horizons advocated by Peach and Horne (1899) (see Section 2.1). The relationship of the Benan Formation to the underlying strata, however, might suggest that the Formation may more properly be excluded from the Barr Group (for reasons outlined in Section 2.7) but this would require a large scale revision of Girvan stratigraphy beyond the scope of the present work.

In the scheme proposed herein the Barr Group is divided into three formations as shown in Figs. 2:2 and 2:3. The sequence is typically developed in Benan Burn and the adjacent hillsides; conformation of the exposed sequence is provided by the I.G.S. Benan Burn Borehole (Fig. 2:3 and Appendix II). Additional exposures necessary to illustrate lateral facies changes are described in the appropriate sections.

2.4.2 Kirkland Formation

The Kirkland Formation (Thickness: 0-280m) comprises all clastic and related carbonate units occurring below the base of the Stinchar Limestone Formation as shown in Fig. 2:2.

Type sections

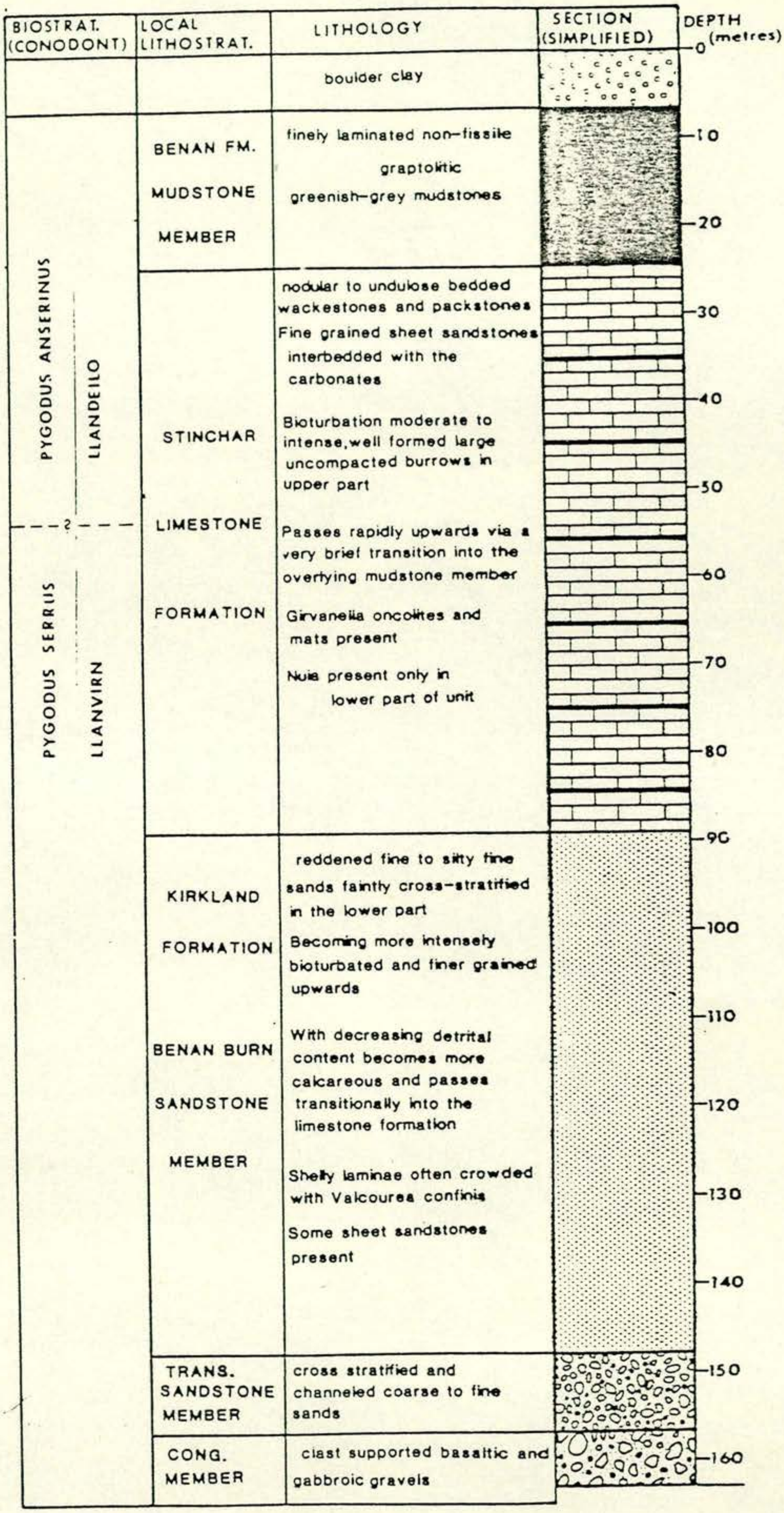
Lateral facies changes within the formation necessiate the nomination of two type sections as follows:

(a) Kirkland Burn

A thick 150m sequence of pebble to boulder conglomerates assigned to the Conglomerate Member outcrops in the stream bed and valley sides above Kirkland Farm. The succeeding Transitional Sandstone Member, consisting of cross stratified sands disposed in conglomerate-based fining-upwards cycles, replaces the Conglomerate Member sequence, outcropping in a narrow gully immediately upstream from the larger of the two waterfalls in Kirkland Burn. The Transitional Sandstone Member passes gradationally upwards into bioturbated silty fine sands of the Benan Burn Sandstone Member which

Figure 2.3

Simplified stratigraphy of the Benan Burn Borehole.



continue to outcrop in the stream bed until the obvious base of the Stinchar Limestone Formation is reached.

(b) Auchensoul Burn

The topmost horizons of the Conglomerate Member, outcropping in the bed of Auchensoul Burn 50m upstream from Auchensoul Farm, are directly overlain by a thin (2.0-2.5m) development of sandy algal carbonates constituting the Auchensoul Limestone Member. The irregular top to the carbonate unit is marked by a cobble horizon which passes upwards into 1-2m of cross stratified sand constituting the local development of the Transitional Sandstone Member. The Benan Burn Sandstone Member is represented by 2-3m of reddish-grey fine sands with mudstone and shelly horizons, and this in turn grades into muddy, thin bedded, limestones of the Stinchar Limestone Formation.

2.4.3 Conglomerate Member

Previously: Purple (or Kirkland) Conglomerate, Lapworth 1882, Peach and Horne 1899.
Kirkland Conglomerate, Williams 1962.

Type Section: Kirkland Burn

Thickness: in excess of 150 metres

Description: Poorly stratified, clast supported pebble to boulder conglomerates with lensoidal sandstones and rare mudstone horizons, outcropping in Kirkland Burn and adjacent slopes up to the large waterfall. Matrix and clast surfaces reddened. Clasts dominantly basaltic in composition, chert, gabbro, serpentinite and a distinctive alkali feldspar syenite also occur. The characteristic lithologies of the Stinchar Limestone Formation and the pink unaltered granite cobbles typical of Benan Formation conglomerates are not seen in the Kirkland clast populations.

Discussion: The proposed unit represents a return to the original definition of Lapworth (1882), and separates the thick conglomerate sequence from the overlying sandstones (Transitional Sandstone Member) included by Williams (1962) in his Kirkland Conglomerate.

2.4.4 Transitional Sandstone Member

Previously: Transitional sandstones and grits, Lapworth 1882, Peach and Horne 1899.
Kirkland Conglomerate, Williams 1962.

Type Section: Benan Burn, stream section above large waterfall at the N. end of the wooded glen.

Description: Approximately 8m thick sequence of reddened cross-stratified sands, occurring as conglomerate based fining upwards cycles. Bioturbation minimal, primary sedimentary structure, undisturbed burrow traces scarce, no body fossils recovered.

Discussion: As with the Conglomerate Member the proposed unit brings back Lapworth's (1882) terminology. As discussed in Chapter 3, the Member represents a distinct set of related depositional environments and is therefore considered to be a valid stratigraphic unit despite limited value as a mappable division due to poor exposure.

2.4.5 Benan Burn Sandstone Member

Previously: Orthis confinis flags, Lapworth 1882,
Peach and Horne 1899. Peach and Horne 1899.
Confinis Flags, Williams 1962.

Type Section: Benan Burn, stream section beginning where the cross stratification typical of the Transitional Sandstone Member is no longer seen. The somewhat scanty natural section is supplemented by I.G.S. Benan Burn Borehole, depths 89.10-148m below surface.

Description: Approximately 50m thick sequence of silty fine sands, reddened in lower part of the Member,replaced by greenish grey colouration towards the top of the unit. Body fossils occur in shelly horizons, bioturbation moderate, both horizontal and vertical burrow traces preserved. 'Pebble trains' overlain by 3-5cm thick rippled horizons occur in the lower part of the Member. Sheet sandstones may be recognised throughout the Member.

Discussion: The Member differs only in name from those previously established by Lapworth and Williams. The existing names are however thought to be inappropriate for the following reasons. Valcourea (Orthis) confinis, from which the unit name was formerly derived has been found as high as 6.5m above the base of the Stinchar Limestone Formation in Minuntion Quarry. Therefore whilst the fossil may be indicative of the unit, it can be assumed to have little biostratigraphic worth, in local correlation. Furthermore, a number of species of Valcourea described by Cooper (1956) from strata as young as Llandeilo in age may be represented among collections made by the author, although further work is needed to confirm this.

2.4.6 Auchensoul Limestone Member

Previously: Auchensoul Limestone, Williams 1962.

Type Section: Auchensoul Burn, 50m upstream from Auchensoul Farm.

Description: Variably reddened, impure, either sandy or muddy, algal limestone, immediately overlying the Conglomerate Member in the type section. Algal genera present include Girvanella as in situ growths, Sphaerocodium, Nuia and the foraminiferid Wetheredella also occurs. The unit is variable in thickness and sporadically developed, 2.0-2.5m in the type section, 7-8m in the overgrown quarry on Doularg Hill but occurs only as thin horizons in the bed of the R. Stinchar above Auchensoul Bridge. The member is absent from the Benan, Kirkland and Kirkdominae sections.

Discussion: The member is interpreted as a lateral equivalent of the Transitional Sandstone Member, the Benan Burn Sandstone Member and also interdigitates with the Auchensoul Bridge Mudstone Member.

2.4.7 Auchensoul Bridge Mudstone Member

Previously: Not recognised as a stratigraphic unit.

Type Section: Bed of R. Stinchar, section starts 20m above the bridge serving Auchensoul Farm.

Description: Reddish grey and greenish-grey silty, calcareous, mudstones in places. Reddened algal carbonate horizons up to 1m. thick occurring within the Mudstone Member are correlated with the Auchensoul Limestone Formation, following Williams (1962). The mudstones are fossiliferous at certain horizons, yielding V. confinis (Williams, 1962, p.11), bands rich in gastopods, sponges and algae, including the red alga Solenopora, also occur. The top of the 30-35m thick sequence is not seen due to lack of exposure; definite representatives of the Stinchar Limestone Formation which would be expected to succeed the member, are not exposed.

Discussion: The member interdigitates with the Auchensoul Limestone Member and is thought to be a lateral equivalent of the Transitional and Benan Burn Sandstone Members.

2.5 Stinchar Limestone Formation

The Stinchar Limestone Formation as proposed consists solely of the algal-rich limestones and associated clastic deposits that either demonstrably overlie the Kirkland Formation or, as far as evidence permits, can be assumed to have originally done so. This definition is in accordance with Williams'(1962) usage of the term Stinchar Limestone, but differs from Lapworth's (1882) Stinchar Limestone Group, in that the 'Orthis confinis flags' and 'Didymograptus shales' are assigned to different stratigraphic groups.

Three sub-units are recognised within the Formation:

Stinchar Valley Member
Tormitchell Member
Brochloch Member

Each member has a distinct environmental significance, although the Stinchar Valley Member is the only one of value as a mappable unit.

Type Section: The outcrops in Benan Burn which Lapworth (1882) and Williams (1962) nominated as a type section for the Barr Series as a whole are currently not well enough exposed to be used as a type section for the Stinchar Limestone Formation. It is therefore proposed that core recovered from I.G.S. Benan Burn Borehole between depths 25.00 and 89.00 metres be considered as the type section for both the Stinchar Limestone Formation and the Stinchar Valley Member of the Formation. A graphic log of the relevant column is presented in Fig. 2:3, based on the log data in Appendix II.

Thickness: 64.00 metres.

Description: The base of the Formation in the type section is gradational and therefore somewhat arbitrary, but is taken to occur where the carbonate content is sufficient for the rock to be termed limestone. The lower part of the unit is composed of variably bioturbated, medium grey, argillaceous algal wackestones, nodular or planar bedded with interbedded siltstones. Sheet sandstones up to 25cm thick occur throughout the section. The central part of the sequence is typified by heavily bioturbated, generally non-nodular, indistinctly bedded muddy wackestones. Planar bedded, pale grey, relatively pure, algal wackestones with occasional nodular horizons, characterise the upper parts of the member. Large, recrystallised, laminar, encrusting organisms, probably either stromatoporoid or coral, and teepee structures, appear to be confined to the upper part of the unit.

Discussion: The designation of a type section for the Stinchar Limestone Formation is perhaps only of limited worth for only in the exposures along the N. side of the Stinchar Valley is there any degree of similarity with sections previously described as typical. Elsewhere lateral facies changes are so striking, both in terms of sequence and of depositional environment, that detailed stratigraphic correlation is difficult. The degree of dissimilarity between the major subdivisions of the Formation and the importance of sub-units within these divisions creates problems for any stratigraphic scheme. These problems are particularly apparent in the Tormitchell Member (see Section 2.5.2) where distinct lithologic units within the sequence are of a magnitude that would normally warrant member status, yet the limitations of the hierarchical scheme do not allow this. Therefore sub-units of the Tormitchell Member are not formally recognised but are termed facies in a strictly lithologic sense, to do otherwise would necessitate too great a departure from the well known existing stratigraphic format.

Outcrops of Stinchar Limestone Formation carbonates are often of a small scale or fragmentary nature or are geographically isolated. In assigning localities to a given member within the formation those exposures whose affinities are uncertain and have no confidently determined environmental significance are not included in the proposed scheme.

2.5.1 Stinchar Valley Member

A type section for the member has already been nominated and described in section 2.5. Similar sequences and lithologies occur in other sections and isolated exposures along the N. side of the Stinchar Valley show little lithologic variation, apart from a decrease in thickness and increased mud content seen at Auchensoul and Minuntion.

2.5.2 Tormitchell Member

Type Section: East face of Tormitchell Quarry.
The base of the section is marked by a faulted contact with fine

grained turbidites assigned by Williams (1962) to the Ardwell Formation. Topmost horizons of the member are best exposed in the S. face of the quarry. Although quarry faces are transient features, the present owners, as far as can be determined, do not plan to extend the workings in a direction that would affect the East face.

Description: Three sub-divisions, informally termed facies, are recognised within the member:
Facies A. Basal sequence, 10-12m thick, of thinly bedded (3-4cm) lithic calcarenites, bedding disturbed at certain horizons. Abundance and grain size of detrital material decreases upwards with a corresponding increase in bioclastic material.
Passes rapidly into
Facies B. 30m thick sequence of wackestones and packstones. Thin bedded and nodular at base and top of the unit, becoming planar, more thickly bedded in the central part of the facies. Oncolites, gastropods and foraminiferids, abundant in nodular and thin-bedded horizons, occur only as discontinuous lenses within the more thickly bedded parts.
Passes gradationally, via a thin sequence of thickly bedded packstones into
Facies C. Massive oolitic grainstones, lacking any recognisable stratification, approximately 20m thick, true top to the unit is not seen.

2.5.3 Brochloch Member

Type Section: Brochloch main quarry.

Description: 15m thick sequence of limestone horizons up to 2m with faintly laminated silty mudstones up to 3.5m. Limestone horizons disrupted, brecciated in appearance, 'clasts' may have rounded appearance. Non-carbonate clasts, basic, ultra-basic and chert up to cobble size are locally abundant. Horizons of limestone pebbles occur in the mudstones. The limestone/mudstone sequence passes into a limestone clast breccio-conglomerate within which non-carbonate clasts become increasinly important upwards.

2.6 Benan Formation

Previously: Benan (or boulder) conglomerate, Lapworth 1882, Peach and Horne 1899,
and
Didmograptus shales, Lapworth 1882
superstes mudstones, Williams 1962.

Excavations made below the crags overlooking the top of Benan Burn indicate that the above two units have an intercalatory relationship with each other, at least in the upper part of the mudstone member. At Auchlewan (NX29 2295 9185), the Conglomerate Member can be seen to rest directly upon Stinchar Limestone Formation carbonates, the contact being an erosional unconformity. The transition from the Stinchar Limestone Formation as seen in the I.G.S. Benan Burn Borehole is rapid, occurring within 1-1.5 metre interval of core, indicating a dramatic change in depositional style.

For the above reasons the Mudstone Member is thought to be associated temporally and environmentally with the Conglomerate Member rather than the Stinchar Limestone Formation, as proposed by Lapworth (1882) and Williams (1962). The two units are therefore grouped together in the same Formation.

2.6.1 Mudstone Member

Type area: The lower boundary of the Member is not naturally exposed. Core recovered from I.G.S. Benan Burn Borehole (depths 25.00 to 6.57 metres) is proposed as the main reference section, the lower boundary and major part of the unit being represented. In addition the crags above Benan Burn (NX29 237 926) are proposed as a reference area, displaying the upper boundary of the unit and its relationship to the Conglomerate Member.

Thickness: 0-25.00 metres thick.

Description: Sequence laminated, non fissile, dark grey to medium grey mudstone with silty laminae, 1-2mm in thickness, sometimes poorly graded. Carbonate concretions may occur, these yielding a diverse trilobite fauna (Tripp 1976). Elsewhere the macrofauna is generally scarce and non-calcareous, consisting of graptolites, horny brachiopods and hyolithids.

2.6.2 Conglomerate Member

Previously: Benan Conglomerate

Thickness: 180'-2,100' (Williams 1962).

Type area: As the Conglomerate Member has not been studied in detail it is not appropriate to designate a type section. Instead it is proposed that, until such time as a detailed study has been carried out, outcrops between the upper reaches of Benan Burn and Auchlewan be used as a type area. This allows recognition of differing relationships with underlying strata shown by lower horizons of the unit. Higher levels of the unit are sporadically exposed around Benan, Kirkland and Auchensoul hills.

Description: Pebble to boulder conglomerate, clasts variably rounded, dominantly basaltic in composition. Chert clasts moderately abundant, basal horixons may be composed almost solely of clasts of Stinchar Limestone Formation carbonates. Distinctive red granites, giving an Rb/Sr age of 460 my (Longman et al. 1979) also occur. Matrix sandy, green, chloritic, weathering with a faint reddened tinge. Stratification poorly developed. Thin units of limestone containing abundant algae and in places corals are seen in certain sections. The unit is widely developed in the Girvan area, thickness being dramatically variable, reaching a maximum in the Water of Assel (Williams 1962).

2.7 Non-assigned localities

Dupin

West of Brochloch Stinchar Limestone Formation carbonates are exposed in stream sections S. of the Water of Assel near Dupin Farm (Fig. 4:4). These sections are generally fragmentary of significantly affected by faulting. Lithologies present are generally nodular or rubbly argillaceous limestones, outcropping above greenish-grey sandstones and pebble conglomerates thought by Williams (1962) to represent a conglomeratic facies of the Stinchar Limestone Formation. The rubbly limestones are overlain by cobble conglomerates of the Benan Formation. The only complete section through the Stinchar Limestone Formation in this area occurs in Dupin Glen where conglomerates and Sandstones occur at the base of the sequence, in the same stratigraphic position as the Kirkland Formation, below a moderately well developed unit of thin bedded limestones belonging to the Stinchar Limestone Formation. The sequence as a whole is strongly reminiscent of those along the Stinchar Valley, however, the sheet sandstones seen in virtually all Stinchar Valley Member outcrops are absent.

Shalloch Hill area

Structurally complex outcrops of sandy limestones, assigned by Williams (1962) to the 'confinis flags' and lower part of the Stinchar Limestone, occur in close proximity to Ballantrae Complex rocks, around the base of Shalloch Hill, Fig. 4:9.

Lendal Valley

Williams (1962), interpreted conglomerates, siltstones and limestones outcropping along the S. side of Lendal Valley as lateral equivalents of the 'superstes mudstones'. Few of these localities are still available due to afforestation and quarry infilling. Figure 2:4 summarises lateral changes in sequence shown by sections accessible in 1972, diagram after Jones (1978).

Craigneil and Bougang

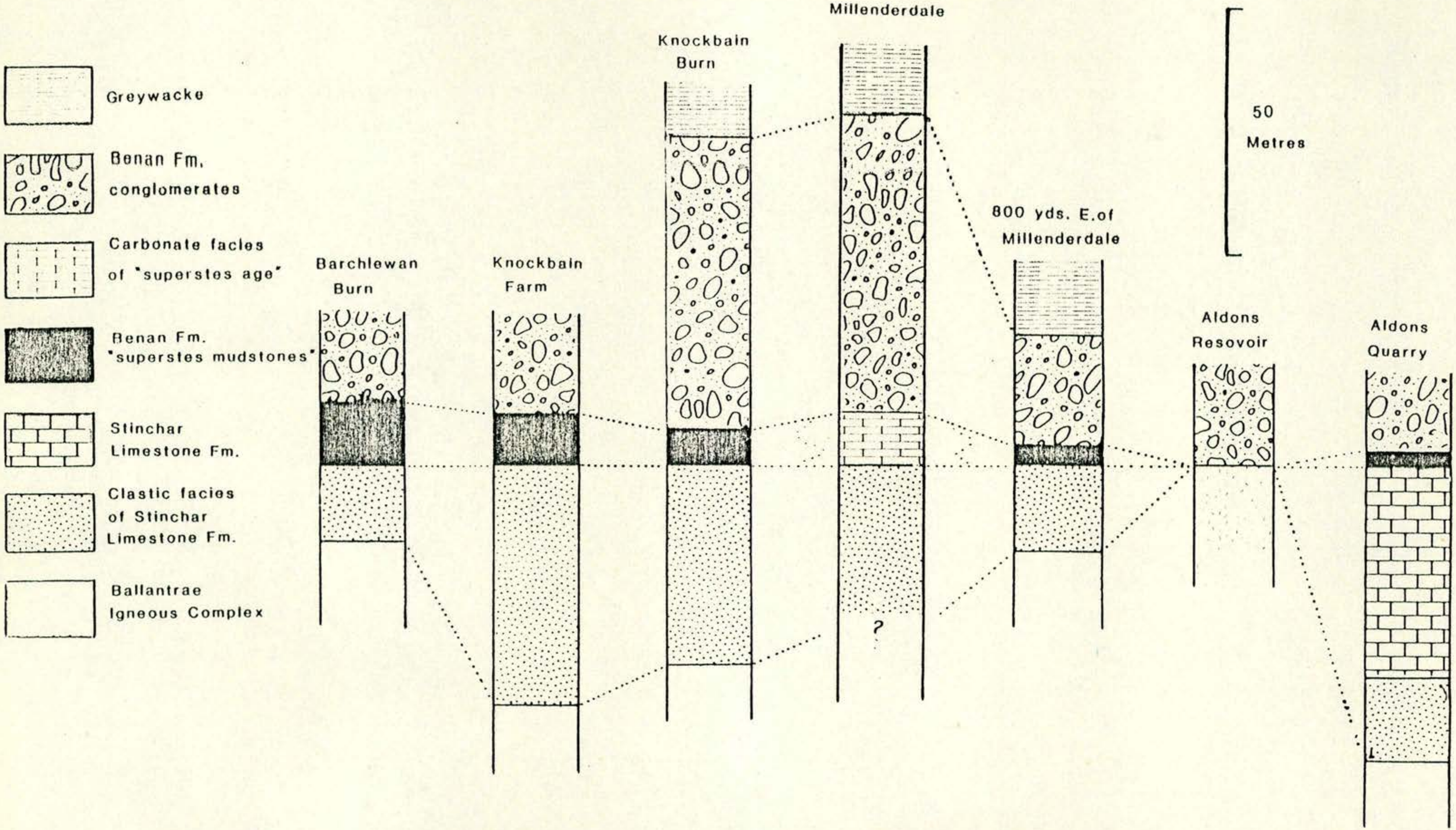
Access to exposures in the quarry below Craigneil Castle is no longer possible due to refuse dumping, in addition other localities in the Colmonell area are too poorly exposed for a stratigraphic sequence to be established at the present. Williams (1962) and Tripp et al (1981) report a 200m thick sequence of calcareous mudstones and sandstones outcropping in the Colmonell area these supposedly being correlatives of the Barr Group. Certainly, the occurrence of Valcourea confinis and other distinctive faunal elements at Colmonell indicates a degree of contemporeity with the Barr Group, but evidence for contiguity is lacking. Similarly, outcrops at Bougang Farm are too poorly exposed for stratigraphic purposes, other than a suggestion that they might correlate with the 'confinis flags' (Williams, 1962, p.21 and Pl. 1).

Aldons

Above Laigh Aldons a carbonate sequence ascribed to the Stinchar Limestone Formation outcrops in two disused quarries, disposed in a

Figure 2.4

Stratigraphy of Localities in the Lendal Valley.



faulted syncline (Williams 1962). A thin sequence of granule and pebble conglomerates, sands and grits unconformably overlies Ballantrae Igneous Complex lavas, the contact being seen in the small stream flowing S. into the more northerly of the two quarries. No definite correlatives of the Kirkland Formation are seen. The thick unit of thin bedded wackestones is muddier than Stinchar Valley Formation limestones, sheet sandstones are absent. As the locality is isolated from Stinchar Valley exposures and no distinctive depositional environment seems to be represented, the locality is assigned broadly to the Stinchar Limestone Formation rather than to a particular member, and is not given member status in its own right.

The limestone sequence passes rapidly upwards into Benan Formation mudstones which at this locality contain carbonate concretions. Conglomerates of the Benan Formation overly the mudstones, in the core of the syncline.

CHAPTER 3

KIRKLAND FORMATION

3.1 Conglomerate Member

3.1.1 Introduction

Outcrops of rudites assigned to this unit are restricted to the northern side of the Stinchar Valley (see map, Fig. 1.3 The unit is best developed in Benan Burn and the adjacent hillsides, where a probable minimum thickness of 200m is displayed, but the exposed thickness decreases laterally, both eastwards and westwards, along the valleyside. The North-South extent of the unit is difficult to determine. To the S. of the Stinchar Valley representatives of the Barr Group, as developed in the type section, are not seen. To the North, sediments of the Barr Group are folded into the Benan syncline (Williams, 1962) in which approximately 500m of Benan Formation conglomerates are preserved, largely obscuring any earlier deposits. Conglomerates underlying the Stinchar Limestone Formation are exposed in those tributaries of the Water of Assel which flow northwards off Benan, Kirkland and Auchensoul hills. Williams (1962) interpreted these as coarse grained lateral equivalents of the Benan Burn Sandstone rather than part of the Conglomerate Member. The relatively thin nature of the sandstone/siltstone sequence exposed in Dupin Glen, intervening between the top of the conglomerate and the base of the Stinchar Limestone Formation compared with the thicker development of these lithologies at comparable levels in sections along the Stinchar Valley, may support this proposal.

Previous authors have interpreted the Conglomerate Member as a slide deposit that accumulated in deep water at the base of a submarine fault scarp (Williams, 1962, Ingham, 1978). This interpretation was based on the opinion of Kuenen (1953) who implied by analogy with the Ventura Basin (Natland and Kuenen, 1951) that the Benan Formation conglomerates (Kuenen apparently did not, however, examine the Kirkland Formation conglomerates) may have been transported by mass movement to water depths of 1-6,000 m. As pointed out by Anderton et al. (1979) this interpretation is in conflict with the occurrence of indicators of a shallow water environment in the Stinchar Limestone Formation. This interpretation also conflicts with the occurrence of algal/foraminiferal limestone horizons within the Benan Formation conglomerates, Chapter 5.

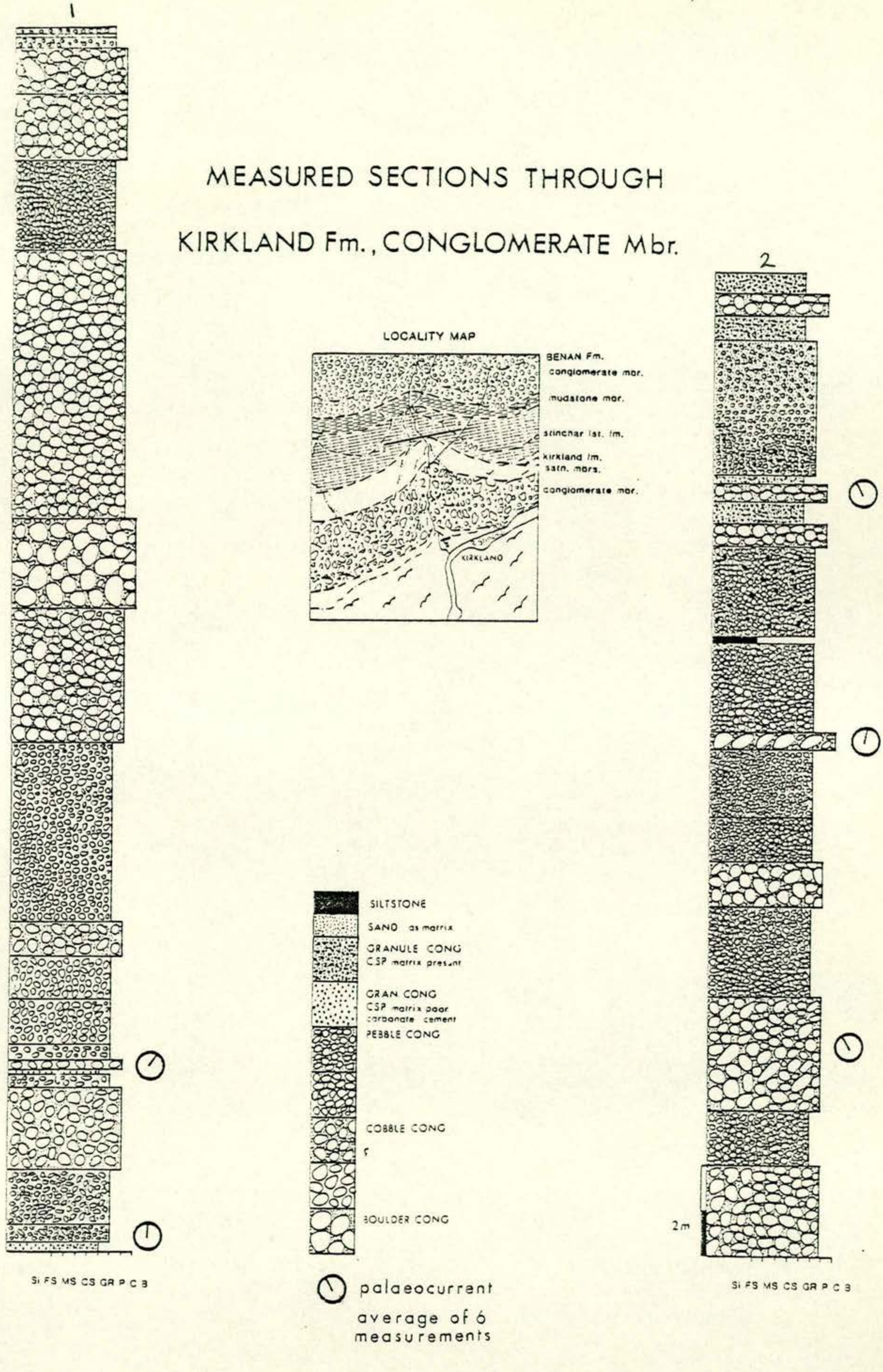
3.1.2 Field description

Only two sections, exposed in Kirkland Burn, are sufficiently well exposed for measurement of useful sedimentary logs, Fig. 3:1. Exposures on Craigbickerae Hill were not measured for safety reasons. A poorly exposed stream section measured in Kirkdominae Burn is shown in Fig. 3:2. The I.G.S. Benan Burn Borehole penetrated the top of the conglomerate Member, and representative intervals are shown in Plates 3:2 and 3:3.

The dominant lithology in the lower of the Kirkland sections is clast-supported pebble to cobble conglomerate, with infrequently developed granule and boulder conglomerate, Plate 3:1, Fig. 1. Bedding is generally indistinct, no grading is seen, clast imbrication is difficult to recognise due to the lack of tabular or discoidal clasts, and is only seen at certain horizons, Fig. 3:1. The clastsare imbricated with their long axes transverse to the direction of dip, indicative of transportation by traction current, rather than any mass transport mechanism (Rust, 1972, 1979, Walker, 1975). Sorting is poor in all conglomerate types, a complete gradation from the maximum particle size down to sand grade material usually being seen. The matrix is reddened, as is a minor, patchy calcite cement (see Section 3 .1.6), but primary mud is absent.

The upper section in Kirkland Burn shows a decrease in the abundance of the coarsest material, cobbles and boulders. Most units are pebble conglomerates, with cobbles occurring either individually or in isolated pockets, Plate 3:1, Fig. 2. The top of the section passes rapidly upwards into the overlying Transitional Sandstone Member. Exposures on the S. side of Craigbickerae Hill are more laterally extensive than those in Kirkland Burn and here the dominant lithology is again poorly sorted, indistinctly bedded, clast-supported pebble to cobble conglomerate with scattered boulders. In addition, lensoidal, laterally thinning, faintly

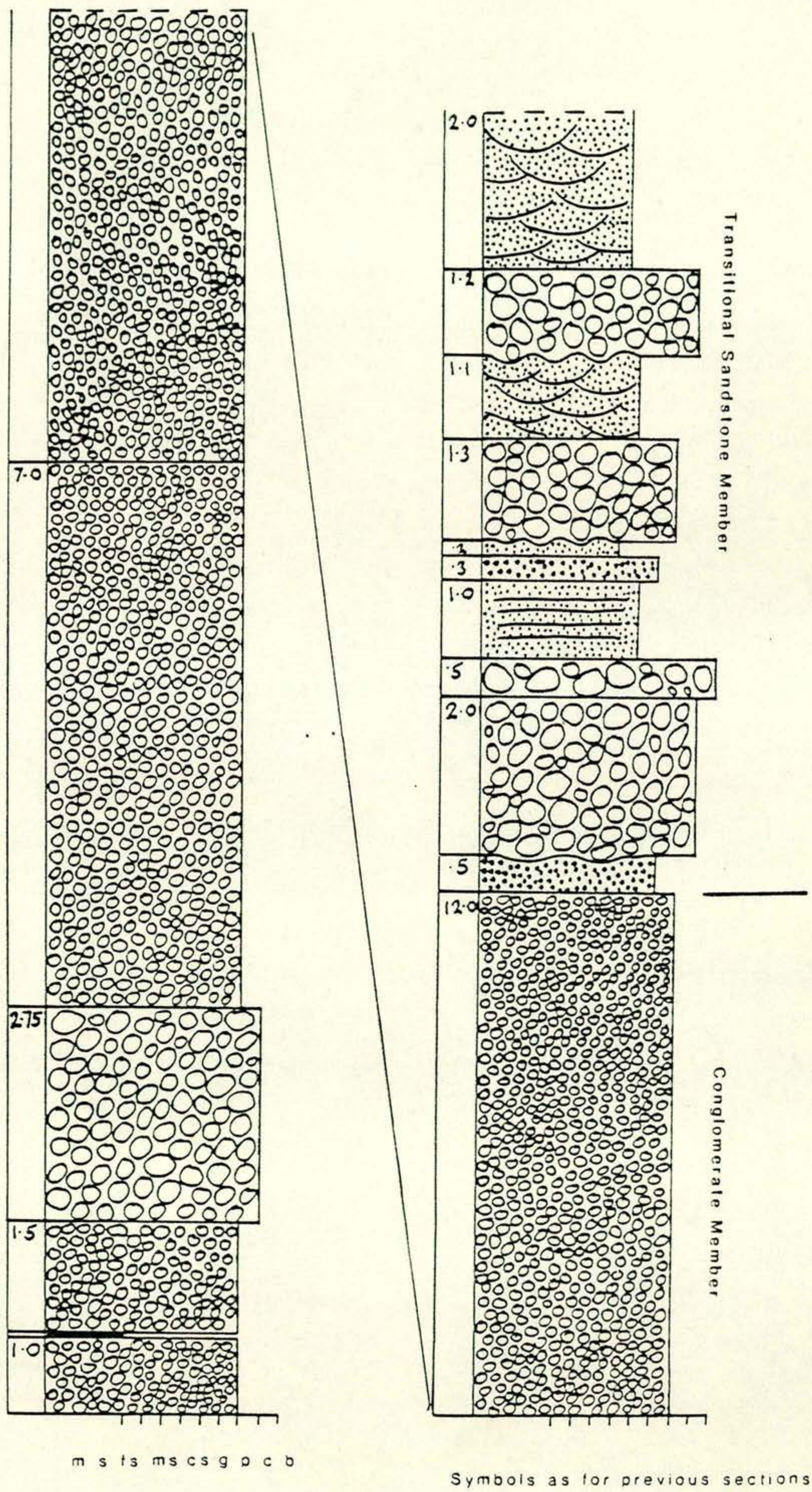
Figure 3.1



MEASURED SECTIONS THROUGH
KIRKLAND Fm., CONGLOMERATE Mbr.
1
2
LOCALITY MAP
BENAN Fm.
conglomerate mbr.
mudstone mbr.
stinchar lst. fm.
kirkland fm.
sstn. mbrs.
conglomerate mbr.
KIRKLAND
SILTSTONE
SAND as matrix
GRANULE CONG
CSP matrix present
GRAN CONG
CSP matrix poor
carbonate cement
PEBBLE CONG
COBBLE CONG
BOULDER CONG
2m
Si FS MS CS GR P C B
Si FS MS CS GR P C B
palaeocurrent
average of 6
measurements

Figure 3.2

KIRKDOMINAE BURN



Symbols as for previous sections

Plate 3.1

Figure 1.

Stratified faintly imbricate pebble and cobble conglomerates in lower part of Kirkland Formation, Conglomerate Member, interbedded with massive, chaotic, cobble and boulder conglomerates, currents flowed from bottom left to top right, approximately N - S in the field.

Locality, Kirkland Burn, (NX29,246 925).

Scale is given by hammer handle (30cm).

Figure 2.

Massive, matrix rich, in places matrix supported, cobble conglomerates in upper part of Kirkland Formation, Conglomerate Member. This lithology is typical of higher levels of the Member along the Stinchar Valley outcrops.

Locality, Kirkland Burn, (NX29,246 927).

Scale as for Figure 1.

Figure 3.

Discontinuous sandstone horizon in upper part of Kirkland Formation, Conglomerate Member. Such horizons may represent low stage infilling of a minor channel within a gravelly braided fluvial system.

Locality, Crags on Craigbickerae Hill, overlooking Benan Farm, (NX29,238 922).

Scale as for Figure 1.

Plate 3.1

Figure 1

Figure 2

Figure 3

Plate 3.2

Cut sections of core through Kirkland Formation, Conglomerate Member, recovered from I.G.S. Benan Burn Borehole. The gravels are dominantly clast supported and are extensively calcite veined.

164·55
164·17
165·43
165·62
165·00
164·55

Plate 3.3

Cut surfaces of core from Kirkland Formation, Conglomerate Member, recovered from I.G.S. Benan Burn Borehole. The gravels are more matrix rich than those shown in the previous plate and occur close to the top of the Member.


10 cm
161·93
162·20
159·95
160·29
157·46
157·89

graded sandstone horizons occur, Plate 3:1, Fig. 3. These are up to 15cm in thickness, extending laterally for up to 4m, thinning and developing a parallel lamination towards the margins. Coarse sands or pebbly laminae define the bases of 2-5cm thick graded units.

3.1.3 Petrography

The most abundant lithologies represented in the clast population at all localities are of basaltic composition. Amygdaloidal lavas, feldsparphyric spilites, microporphyritic basalts and reddened, indurated, basalts are all represented, varying in size from pebbles to boulders. Gabbros form a relatively minor proportion of the clast population and have not been seen to exceed cobble size. Serpentinites are only seen as cobbles and highly altered grains in the matrix. Chert fragments occur as matrix components and as pebbles and more rarely cobbles. Gneissose, variably deformed, granitoids occur most frequently in the boulder and large cobble categories. Isotopic, data obtained from these clasts indicate an age of 648$\pm$ 32m.y. (Rb/Sr) (P. Taylor, pers. comm., 1981).

With the exception of the gneissose material the clast population indicates a local derivation from the Ballantrae Igneous Complex, the predominance of basaltic clasts in the Conglomerate Member reflecting the importance of these lithologies within the Complex.

The matrix is sandy, single mineral grains and lithic grains, both of medium to coarse sand or granule size, are the dominant component (90-95%) with minor percentages of opaque minerals, either magnetite or titanomagnetite. Grain roundness is variable, single crystal grains, usually moderately fresh feldspar, being more angular than the generally rounded lithic grains.

3.1.4 Clast Shape

The shape displayed by a large clastic particle is the product of a number of interacting factors as outlined by Sneed and Folk (1958).

(1) The degree of isotropy or anisotropy exhibited by the material constituting a given clast.

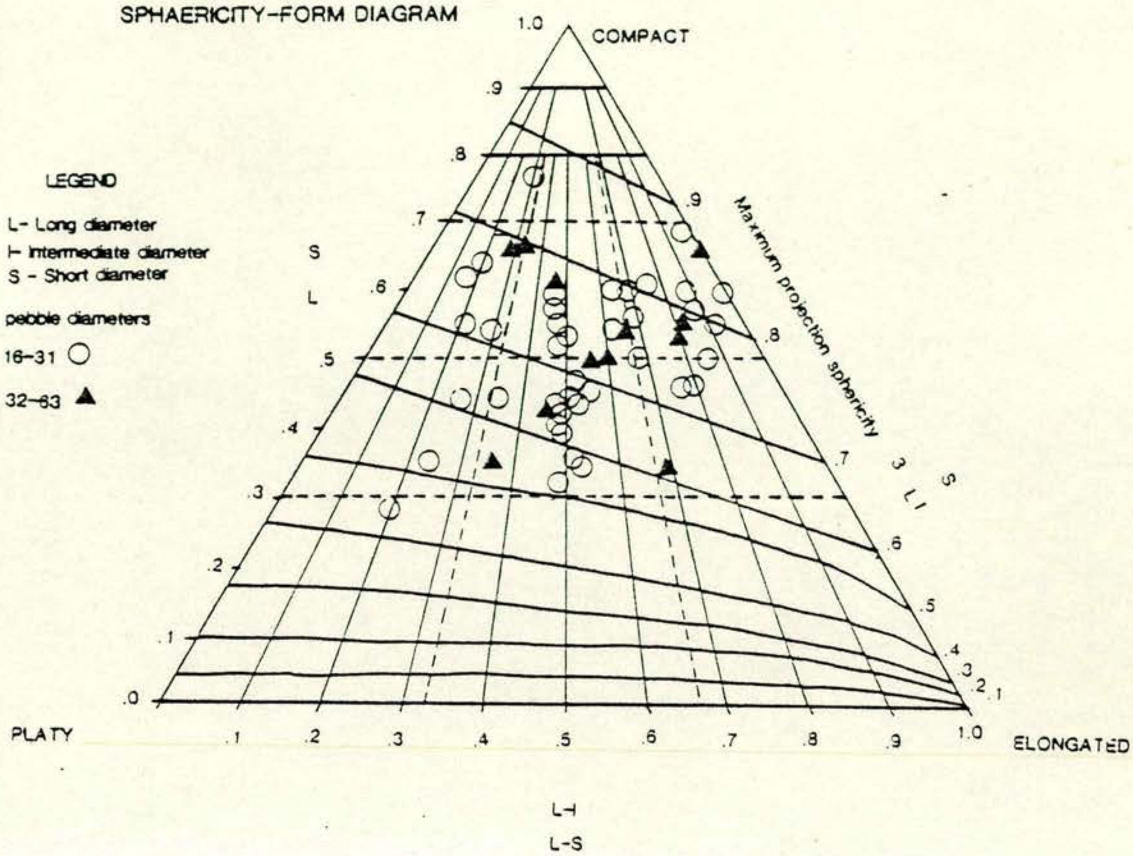
(2) The initial shape of the material before it enters the system(s) in which modification of this shape occurs.

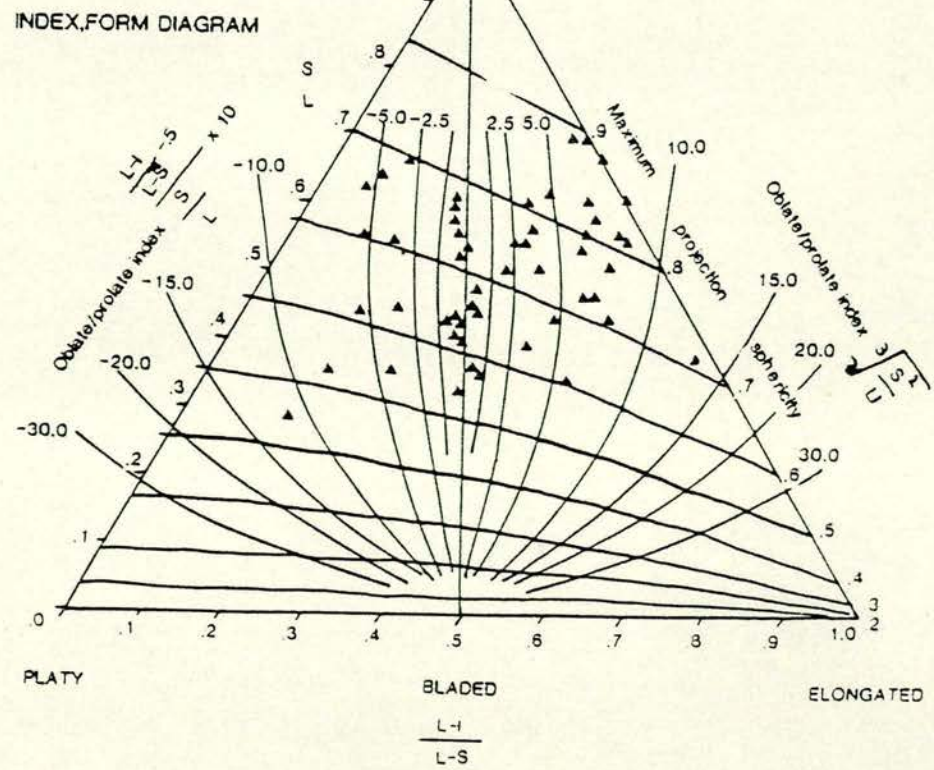
(3) The environment in which the initial shape is modified. Shape has been utilized in discriminating between the redeposited products of rounding in beach or fluvial environments by McBride (1966), and Ricci Lucchi (1969). Carefully controlled studies of basalt pebble shapes in rivers and adjacent beaches on Tahiti-Nui (Dobkins and Folk, 1970) demonstrate that a valid distinction between these two environments can be made.

Shape is essentially a three dimensional property, and as a result the majority of relevant studies have been carried out on unconsolidated material. Assessment of shape in consolidated sediments has usually been highly qualitiative, e.g. Daily et al. (1980) or has been more or less disregarded as a factor in environmental interpretation. The Kirkland Formation conglomerates are well suited to study of clast shape as certain horizons are cemented by vein calcite, samples can therefore be recovered by dissolving the carbonate in weak acid. The dominantly basaltic composition and the chosen clast size, pebble rather than granule or cobble, allows direct comparison with the results of Dobkins and Folk (1970). Material for examination was collected from a discrete horizon of pebble conglomerate at the base of the Kirkland Burn section.

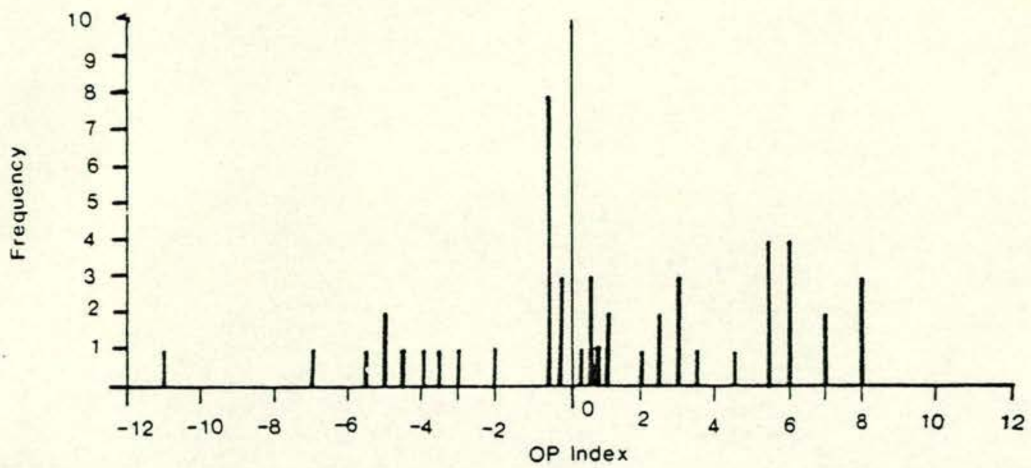
Shape was determined by the method proposed by Sneed and Folk (1958) and used by Dobkins and Folk (1970) involving direct measurement of the three principal, mutually perpendicular, axes. This allows discrimination of shapes into 10 categories and also determination of maximum projection sphericity and oblate- prolate index, as proposed by Dobkins and Folk (1968), a modification of Zingg's (1935) shape classification, allowing a more accurate description of true shape. Data were obtained from 50 pebbles of basaltic composition by direct measurement using Vernier callipers. Clasts having a maximum dimension less than 16mm were not measured, so as not to confuse comparison with the results of Dobkins and Folk (1970), a representative sample of the results were first plotted on the triangular, sphericity-form diagram (Sneed and Folk, 1958), Fig. 3:3a. Seven form classes are present, with a bias towards compact forms. Sphericity is generally high, few clasts having values less than 0.6, the majority being greater than 0.7. Comparison with Dobkins and

Figure 3.3


SPHAERICITY-FORM DIAGRAM
COMPACT
LEGEND
L- Long diameter
I- Intermediate diameter
S - Short diameter
pebble diameters
16-31
32-63
S
L
Maximum projection sphericity
PLATY
ELONGATED
L-I
L-S


SPHAERICITY,OBLATE/PROLATE
INDEX,FORM DIAGRAM
COMPACT
S
L
Maximum projection sphericity
Oblate/prolate index
PLATY
BLADED
ELONGATED
L-I
L-S

a) Oblate/prolate index frequency histogram.



b). SPERICITY vs.O P INDEX

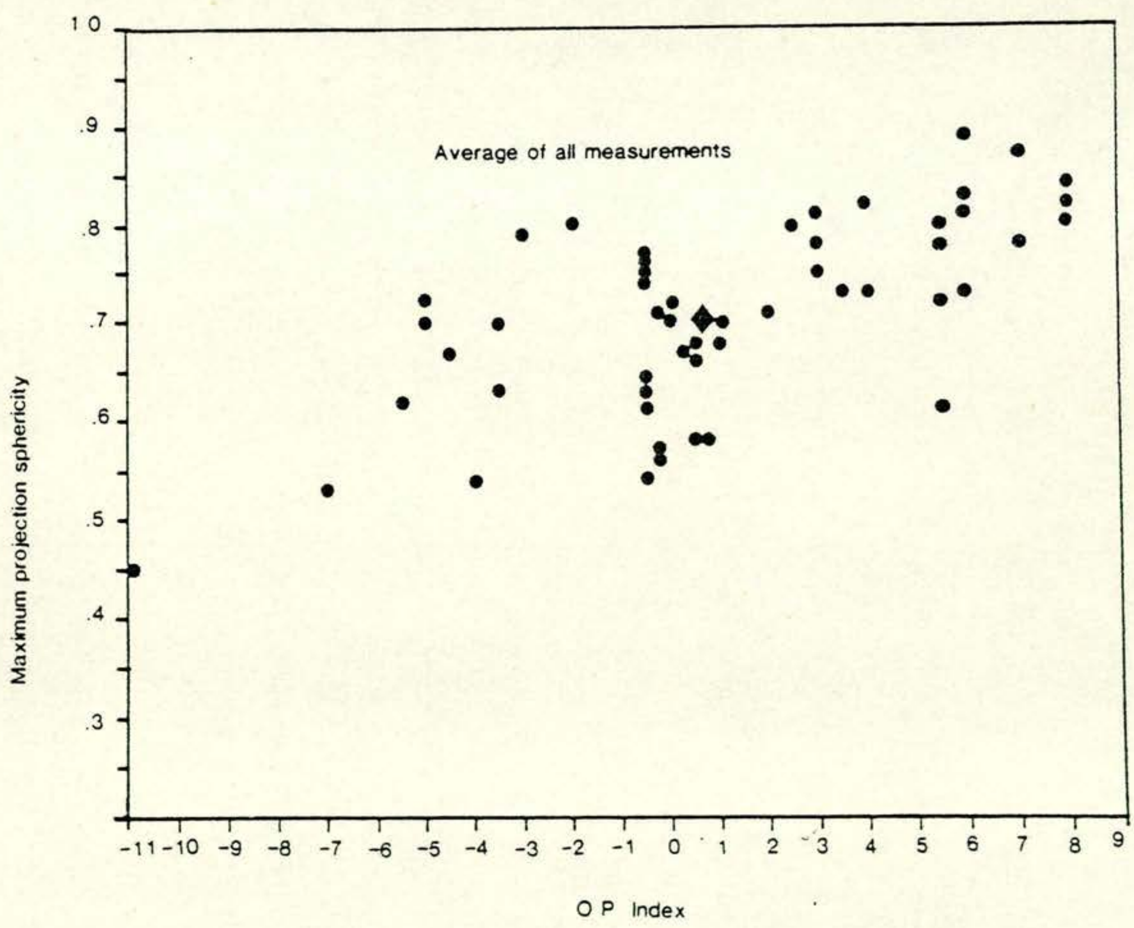


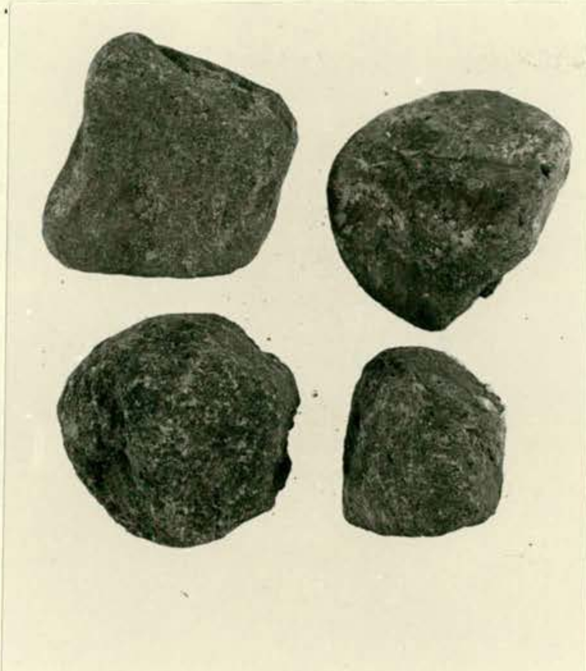
Plate 3.4

Pebbles from Kirkland Formation, Conglomerate Member, used in form analysis.

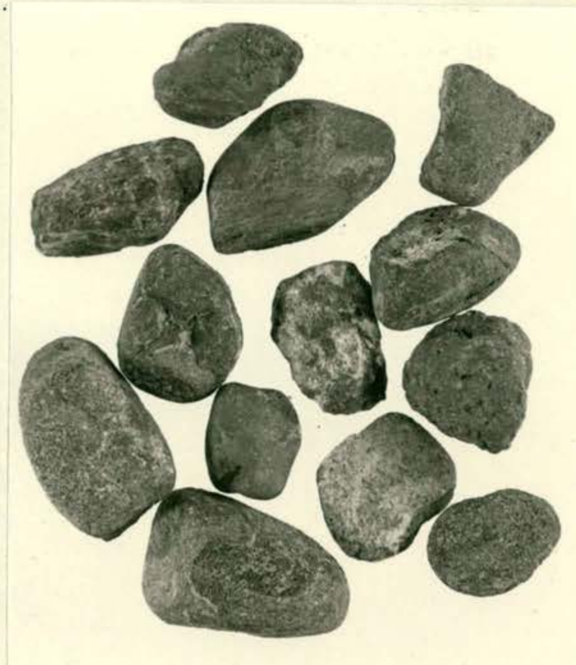
a) 63 - 48mm. b) 47 - 32mm. c) 31 - 25mm. d) 24 - 16mm.

Plate 3.4

a)



b)



c)

d)

Folk (1970, Figs. 16 & 17, p.1186) suggests that fluvial processes were instrumental in producing the sphericity of the Kirkland clasts, the majority of which lie above the environmentally discriminative dividing line of p = 0.65-0.66 proposed by Dobkins and Folk.

Sphericity alone does not adequately define the shape of a pebble, in addition, a measure of the oblateness/prolateness of the clast is needed (Sneed and Folk, 1958). Using a modified sphericity/form diagram Dobkins and Folk (1970) constructed contours of equal oblateness/prolateness. Plotted on this diagram, the Kirkland pebbles show a concentration around the zero line on the OP index of Dobkins and Folk (1970), see Fig. 3:3b, plotted as a frequency diagram, and Fig. 3:4a.

The most effective environmentally discriminative plot, however, is that of OP plotted against λ p, Fig. 3:4b, Comparison with Dobkins and Folk (1970), Fig. 12, demonstrates clearly the affinity of the Kirkland clasts with pebbles on Tahiti-Nui rounded in a fluvial rather than beach environment.

3.1.5 Interpretation and Discussion

As briefly outlined in 3.1.1, previous authors have considered the Conglomerate Member to be a deep water slide deposit (Williams, 1962, Ingham, 1978). Anderton et al. (1979) take this argument one stage further and claim a deep-sea fan setting for the Girvan conglomerates, questioning the shallow water nature of the Stinchar Limestone Formation. In reaching a satisfactory interpretation of the Conglomerate Member it is vital that the Stinchar Limestone Formation also be correctly interpreted. In particular the probable depth at which the limestone accumulated is or prime importance in assessing the most realistic environmental setting for the Conglomerate Member. As demonstrated in Chapter 4, the Stinchar Limestone Formation unquestionably accumulated in shallow water. In the light of this it is felt unlikely that the Conglomerate Member accumulated in deep water. Williams (1962) attempted to resolve these two apparently incompatible lines of evidence by proposing two sources for Conglomerate Member sediments. According to Williams material was supplied from the N. by sliding, prior to which time it accumulated in shallow water above a fault scarp. He also suggested a second sediment source lying to the E. Neither of these explanations is consistent with field evidence, for reasons outlined below.

(1) There is no evidence that Kirkland Formation Conglomerates were 'emplaced' as rigid or semi-consolidated masses along discrete shear planes, and therefore do not conform with the definition of a slide deposit as proposed by Dott (1963), for which the synonymous term olisthanite (Carter, 1975) has later been used.

(2) The degree of organisation seen in the Conglomerate Member gravels as shown by well-sorted pebble and sand horizons, combined with the presence of a clean washed sand matrix lacking mud, militates against a submarine rockfall origin. Such rockfall deposits appear to occur most frequently at the margins of either reefs or carbonate platforms, where angular blocks of shallow water limestones may occur in a matrix of mudstone or other sediment, whose facies is of an appreciably deeper water aspect than the carbonates. Examples of such deposits include a Permian fore-reef talus of W. Texas (Rigby, 1958), the Cow Head Breccia of Newfoundland (Whittington and Kindle, 1958), which Rodgers (1970) considered to have slid down an ancient continental slope in an environment similar to the Eastern edge of the present day Bahama bank.

(3) As outlined in Section 3.1,4, fluvial rather than littoral processes were responsible for the clast shapes seen in the Conglomerate Member. Although transportation of such clasts into deep water regions has been documented by McBride (1966) and Ricci Lucchi (1969), the types of primary sedimentary fabric, such as normally graded or inverse to normally graded, determined to be indicative of resedimented conglomerates (Davies and Walker 1974, Walker 1975, Walker 1978) are not seen in the Kirkland Formation Conglomerates.

(4) Where the rare discoidal clasts are imbricated, they are found with the long axis orientated at 90^{0} to the dip of the AB plane. Davies and Walker (1974) and Walker (1975, 1978) report that imbrication in resedimented conglomerates occurs with the clast long axis parallel to the dip of the AB plane. Rust (1972) demonstrates that imbrication of the intermediate axis is typical of fluvial deposits, as a result of rolling of clasts during transportation by traction currents. Although this difference may not be convincingly significant environmentally (Howell and Link, 1979) imbrication still gives

an indication of both palaeocurrent direction and palaeoslope (Bluck 1974, Rust 1978, Daily et al. 1980).

(5) Resedimented conglomerates occurring in deep sea fans have always been reported to be associated with well developed turbidite sequences, e.g. Ventura Basin, California (Natland and Kuenen, 1951), Cap Enrage Formation, Cambro-Ordovician (Davies and Walker 1974, Walker 1975).

(6) The only evidence put forward by Williams (1962) for an easterly source for part of the Conglomerate Member sediment is based on palaeocurrent data obtained from turbidites than outcrop in the Water of Gregg at a stratigraphic level low down in a sequence assigned by Williams to the Traboyack Formation (Williams, op.cit. p. 64). As discussed in Chapter 6, the strata from which Williams obtained his data represent an environment different not only from the rocks exposed in Kirkland and Benan Burns, but also from those in Traboyack Burn, the type section for the Traboyack Formation. Mineralogical analysis, Chapter 6, shows that the basic and ultrabasic igneous terrain of the Ballantrae Complex probably contributed little detritus to the Gregg Water sediments at this low stratigraphic level. Thus the data of Williams is not felt to be compelling evidence of an easterly source of sediment for the Kirkland Formation Conglomerates.

The palaeogeographic model proposed by Williams (1962) for the Girvan succession, and borne out by the present work, in which synsedimentary fault activity is adduced to be the major factor controlling sedimentary style, coupled with the shallow water nature of the overlying sandstones and carbonates, allows an environmental interpretation of the Formation to be made. It is not, however, possible to reach a definite conclusion regarding overall depositional environment on the basis of observations made solely in the Conglomerate Member, the following features of which are significant.

(1) The Conglomerate Member is an oxidised, reddened, deposit. Reddening in coarse grained deposits is one of the criteria proposed by Bull (1972) for the recognition of alluvial fan deposits, and reported from fan deltas by Link and Osborne (1979), Daily et al. (1980), Winston (1979), Hayward (1982).

(2) The composition and texture of the conglomerates are consistent with the criteria proposed for the recognition of fan-delta deposits by Wescott and Etheridge (1980), and with published descriptions of conglomeratic facies in fan-delta settings, Daily et al. (1980), Erickson (1978), Howell and Link (1979), Link and Osborne (1978).

(3) The tectonic setting of the Girvan succession, interpreted as a fore-arc sequence by Longman et al. (1979) and Ingham (1979), is comparable with tectonic setting of Holocene fan-deltas (Wescott and Etheridge, 1980), although the fan-deltas figured by Holmes (1965, pp.553 & 554) can hardly be said to have developed in this setting.

(4) Clast shape is indicative of a fluvial environment, section 3.1.3.

(5) Primary sedimentary features in the overlying Transitional Sandstone Member indicate deposition from near unidirectional currents flowing in delta-top distributary channels dominated by fluvial processes (Section 3.2.3).

In fan-delta environments the pattern of sedimentation is dominated by fluvial processes in sub-aerial regions, the products of which may be modified by marine processes in transitional (shoreline), and sub-sea environments, Wescott and Etheridge (1980). Criteria for the distinction of marine and non-marine environments in coarse grained, conglomeratic, fan-delta deposits are scarce. Only the recognition of beach gravels, characterised by bed lenticularity and segregation of sand and gravel components (Clifton 1973), or the presence of flaser bedding would provide an unambiguous differentiating factor, as would the presence of either marine or terrestial faunas or floras. In micro-tidal environments, e.g. The Red Sea, the beach zone may be as little as 30cm in total thickness (Hayward, 1982 and Appendix III) and the recognition of such a horizon in an ancient deposit would obviously be extremely difficult. In pre-vegetal deposits there is little likelihood of any fossils indicative of a subaerial environment being recovered. Within the Conglomerate Member no distinction between the two environments can be made, no beach horizons can be recognised, no faunas of any type are present, there does not appear to be any vertical change in clast shape that could indicate the presence of beach rounded material.

Howell and Link (1979) and Link and Osborne (1978) record a rapid decrease in conglomerate abundance from subaerial to subaqueous environments, those conglomerates that do occur are generally mass flow deposits associated with submarine channels. Although there are no documented investigations of present day fan deltas that have attempted to describe changes in process when a coarse sediment laden effluent flood enters a standing body of water it is reasonable to assume that, due to a rapid current deceleration, most of the sediment load would be rapidly dumped giving rise to a disorganised fabric in the deposit thus formed.

In view of the foregoing considerations either or both of two depositional mechanisms are thought to be responsible for the type of facies seen in the Conglomerate Member.

(1) Transportation in the subaerial environment during high energy, stream-flood (Blissenbach 1954) or debris-flood (Miall, 1970) events. Both processes are typified by poorly organised, clast-supported deposits, with a coarse grained matrix lacking a mud component. Alternatively, the generally structureless or crudely stratified nature of the Conglomerate Member gravels may indicate deposition in a coarse braided system as described by Boothroyd and Nummedal (1970) from glacial outwash deposits.

(2) Transportation by any of the above processes in the subaerial environment but with deposition taking place in the submarine environment as a result of current deceleration on entering a standing body of water. The beach zone may have been bypassed or tidal/wave effects may have been slight, to account for the lack of evidence for processes typical of these environments. The proposed depositional mechanisms are consistent with the lack of fine grained, clay or silt, material in the conglomerate matrix. At the current velocities at which cobble or boulder size material is deposited, during waning flood stage (Wolman and Miller, 1960) such fine grained sediment would still be in suspension. Furthermore fine grained sediment may be removed from subaerial areas of fan deltas by aeolian activity, this process being an important factor in the development of present day fan deltas in the Red Sea. (Appendix III). Thus there may be a marked separation, in terms of site of deposition, of coarse and fine grained sediment fractions. In the case of the Kirkland Formation conglomerates the fines are thought to have been deposited as part of the Taboyack Formation, Chapter 6.

3.1.6 Origin of carbonate cements in the Kirkland Formation Conglomerates

As noted by Lapworth (1882), Kirkland Formation conglomerates possess, at certain horizons, a carbonate cement, and also veins of sparry calcite. Recorded instances of carbonate cementation of coarse grained deposits indicate that the beach environments are the most common site in which this process may take place (Bathurst, 1976 and references, Appendix III). Carbonate cemented gravels have, however, also been reported from ancient and recent alluvial fans, associated with playa lakes and evaporite basins (Eugster and Hardie, 1975, Hunt et al., 1966).

N.-S. trending carbonate veins occurring in the Kirkland Formation conglomerates outcrop on the S. face of Cantersty Hill. Vein margins are sharp, and in places both clasts and matrix in the conglomeratic country rock are brecciated, Plate 3:5, Fig. 1. Green coatings on clasts close to the vein margin indicate associated, small scale, copper mineralisation. The vein body broadens downwards, attaining an observed lateral extent of not less than 6 metres. The carbonate forming the vein fill is banded, with brecciation of pre-existing carbonate, denoting forceful, incremental addition of fresh vein material. Small scale linear veins, also trending N.-S., with sharp parallel sided margins also occur, being seen in Kirkland Burn, Plate 3:5, Fig. 2.

In addition to these clearly defined veins, horizons of carbonate cemented conglomerate with diffuse margins also occur. The vein origin of these apparently near horizontal, S.W.-N.E. orientated, strike parallel, horizons is not apparent in field examination.

Carbonate cemented gravels were recovered from the I.G.S. Benan Burn Borehole, the fresh nature of this material renders it suitable for petrographic study.

Examination of intergranular carbonate in the core interval 165.00-164.55, Plate 3:2, allows recognition of the three, sequential, morphologic types of carbonate described below.

Plate 3.5

Figure 1.
Complex calcite veining and associated brecciation in Conglomerate Member. The vein fill is clearly incremental, consisting of a series of thin carbonate bands. This relatively thin vein widens downwards into a major vein complex cutting the Conglomerate Member.
Locality, Cantersty Hill, (NX29,243 924).
Knife gives scale (11cm).

Figure 2.
Parallel sided vein, trending N - S and cutting the Conglomerate Member.
Locality, Kirkland Burn, (NX29,246 927).
Scale is given by pen (15cm).

Plate 3.5

Figure 1

Figure 2

Type 1 carbonate is heavily haematite stained calcite occurring as 'cement' in areas of sandy matrix, Plate 3:6, Fig. 3, and is crosscut by the two later calcite generations, Fig. 3:5.

Type 2 carbonate is clear, non turbid, displays a fibrous habit and occurs in narrow veins with crystal long axes orientated normal to vein margins. The veins show a marked tendency to follow clast margins but may also cross cut clasts, Fig. 3:5, Plate 3:6, Fig. 1.

Type 3 carbonate is the volumetrically most abundant form. It is a nearly opaque, turbid spar with poorly defined intercrystal boundaries, in places showing a poorly developed botryoidal form. This carbonate type is seen to cross cut clasts, Fig.3:5, Plate 3:6, Fig. 1, and all other carbonate types, Fig. 3:5,

In addition to the various carbonate types present the frequent occurrence of clast/clast indentation records another important event in the development of the conglomeratic unit. Indentations are up to 3mm in depth, non stylolitic, usually reflecting the shape of the impressed clast, Plate 3:6, Fig. 2.

The sequence of events affecting the conglomerates can be deduced from date of the type presented in Fig. 3:5, and is summarised in Fig. 3:6.

(1) Deposition of clast-supported, framework conglomerates with coarse sand matrix.

(2) Precipitation of Type 1 haematite stained carbonates. This stage may represent the only cement, sensu Bathurst,(1976) present. The high degree of reddening and the fragmentary preservation of this type of carbonate do not allow the recognition of features proposed by Bathurst (1976) as diagnostic of cement.

(3) Compaction, producing clast/clast indentation, Plate 3:6, Fig. 1. Whether or not this stage preceeds stage 2, is impossible to determine on the basis of evidence available, it would however seem intuitively reasonable to assume that compaction postdates cementation.

(4) Small scale veining by Type 2 carbonates, this stage clearly postdates the compactional event as veins of this type can be seen to separate clasts previously indented into one another, Plate 3:6, Fig. 2.

Sketches of calcite cemented horizons in Conglomerate Member.

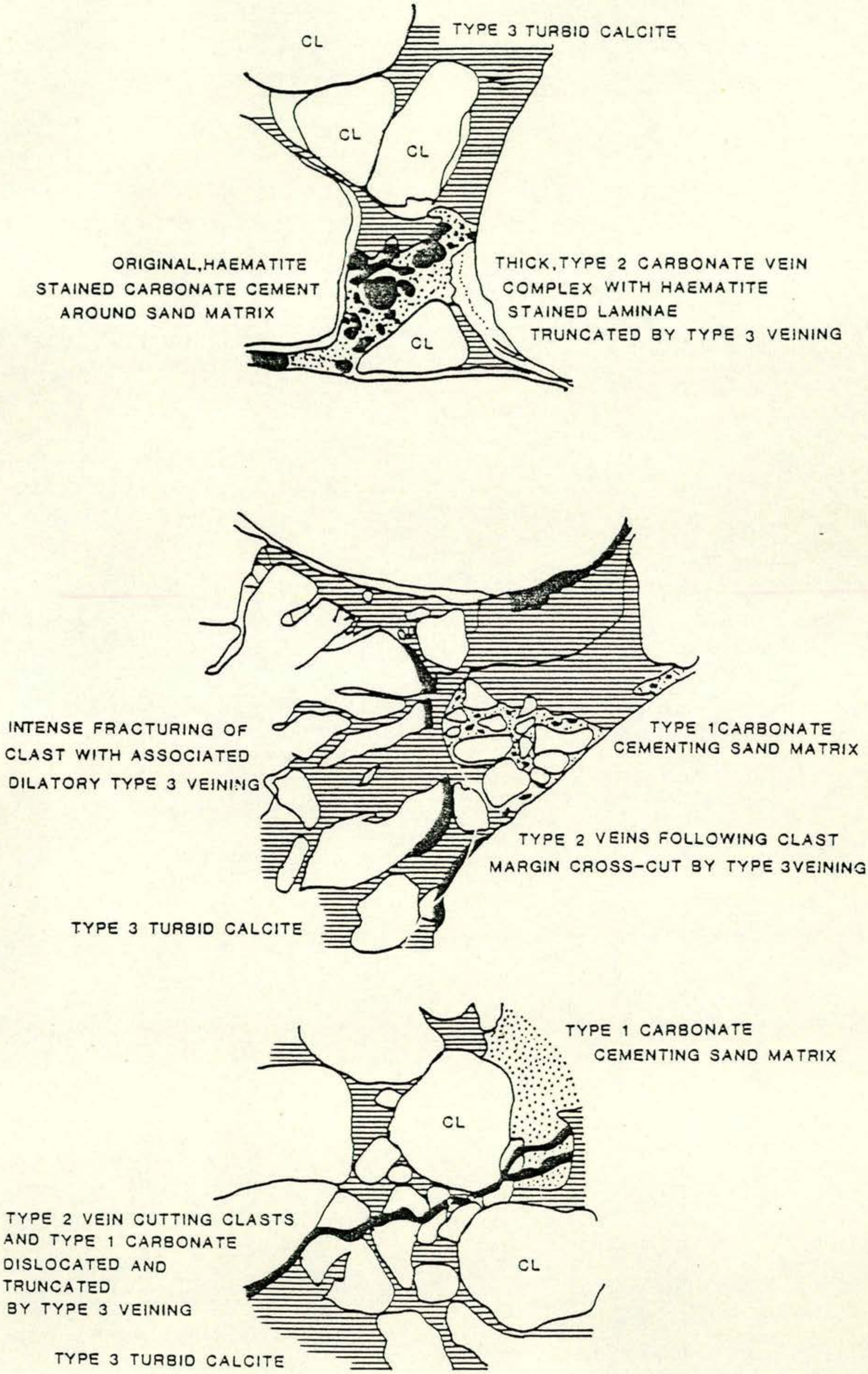


Plate 3.6

Figure 1.
Type 2 carbonate veins (arrowed 2) following clast margins but also cutting through clasts (at a for example). Later, Type 3, vein calcite, is turbid and may show a faintly botryoidal habit and is seen to cut clasts. (e.g. at b)

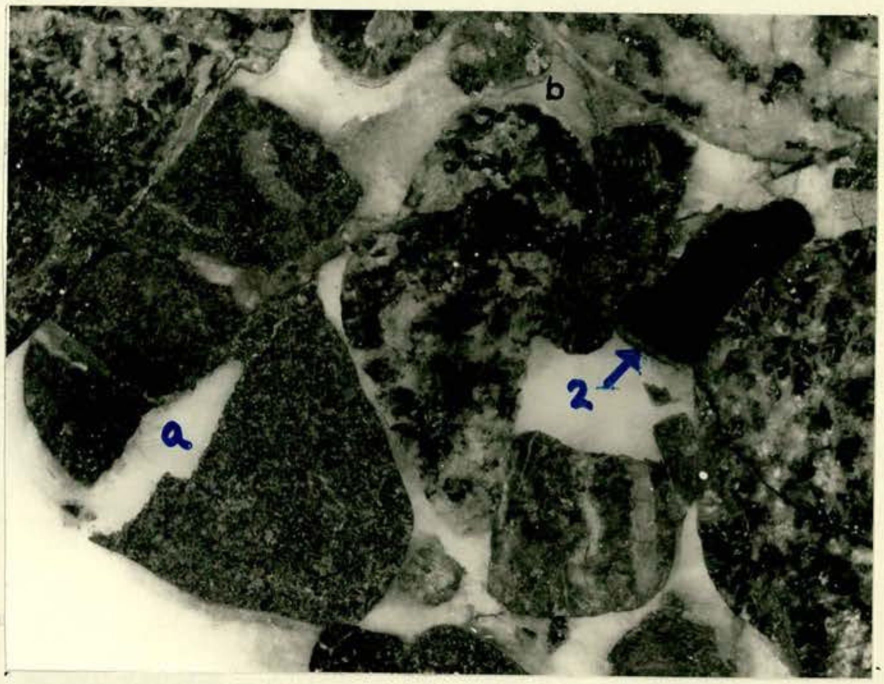
Figure 2.
Indentation of clast margins in pebble conglomerate, the clasts have been separated by a thin calcite vein of Type 2.

Figure 3.
Extensive veining of pebble conglomerate by Type 3 calcite. Remnants of Type 1 calcite cement can be seen. (e.g. at a)
Scale on left is in 1cm divisions.

Plate 3.6

Figure 1

1cm



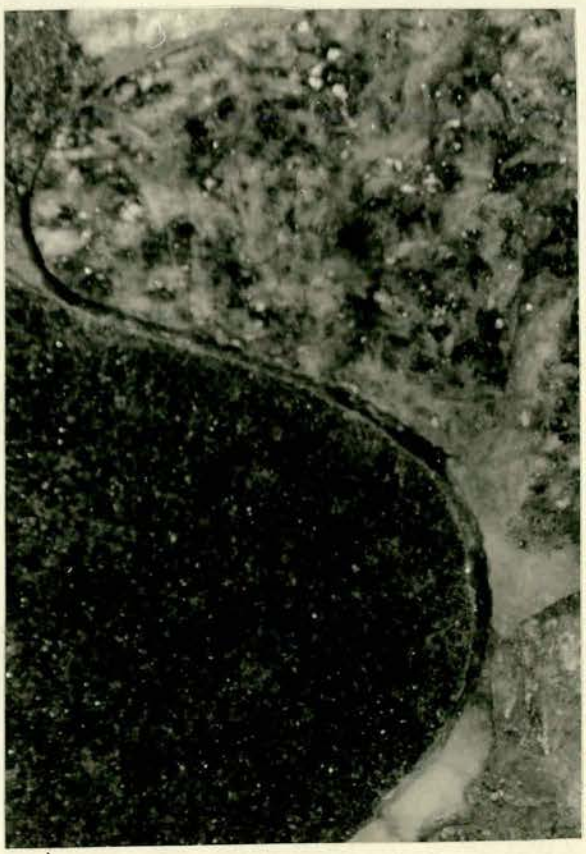


Figure 2

1cm

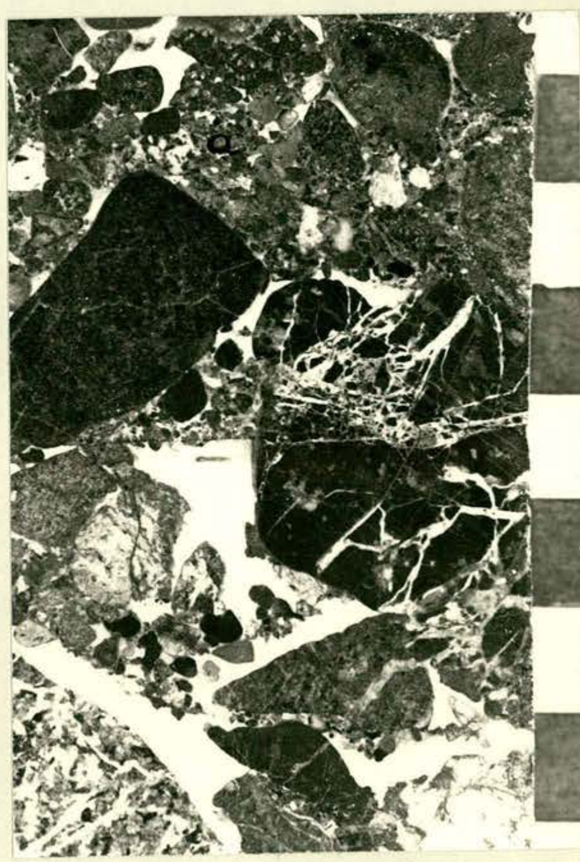
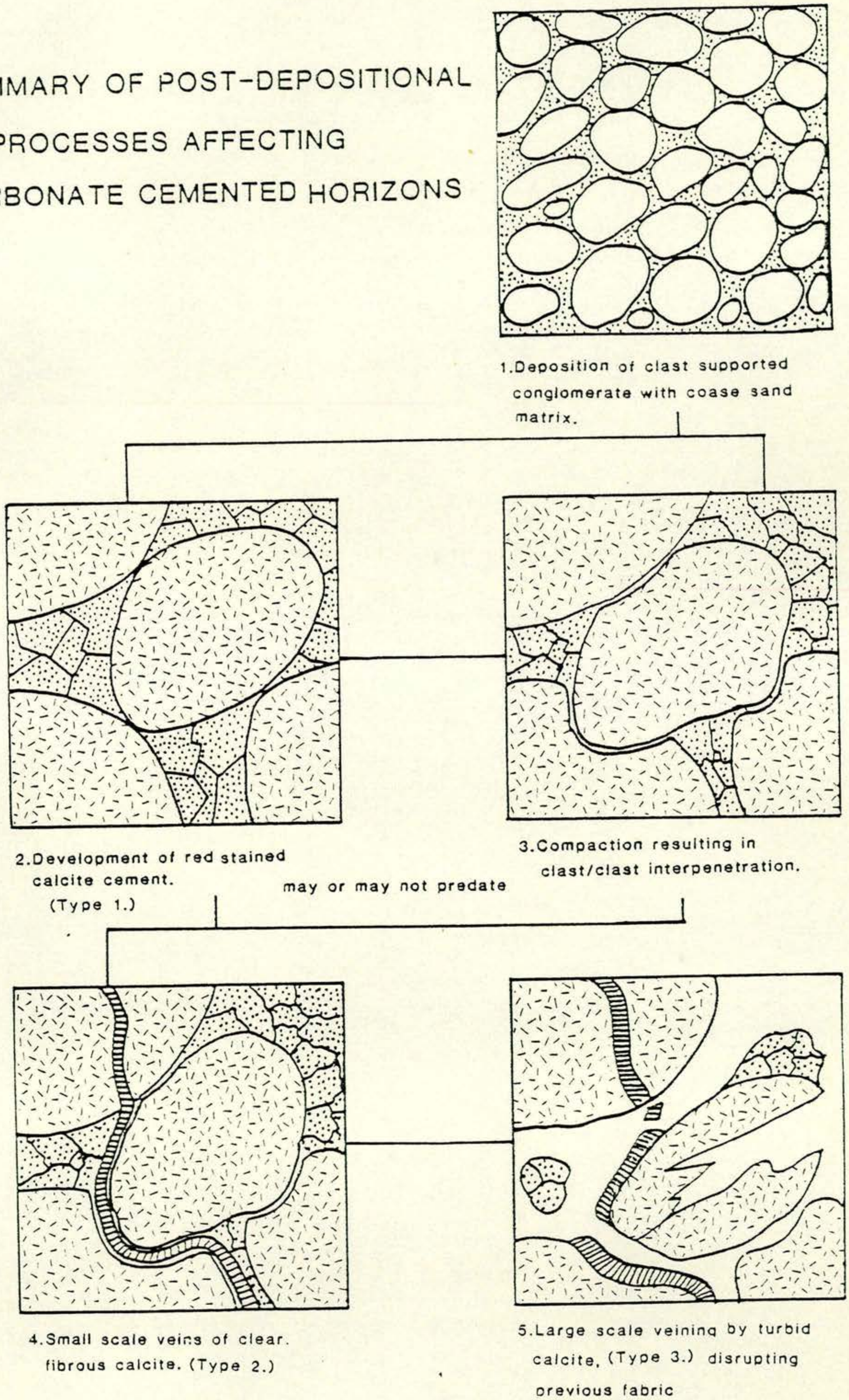


Figure 3

Figure 3.6

SUMMARY OF POST-DEPOSITIONAL PROCESSES AFFECTING CARBONATE CEMENTED HORIZONS



(5) Large scale veining by Type 3 carbonates, producing a more open fabric than originally developed by depositional processes, Plate 3:6, Fig. 3 and Fig. 3:5. The bulk of carbonate in the Kirkland Formation conglomerates cannot therefore be explained by a normal process of cement precipitation, and is therefore not environmentally significant. Such veins are most probably related to the Formation of a N.-S. trending tension joint system of 'Caledonian' age recorded by Williams (1959).

3.2 Transitional Sandstone Member

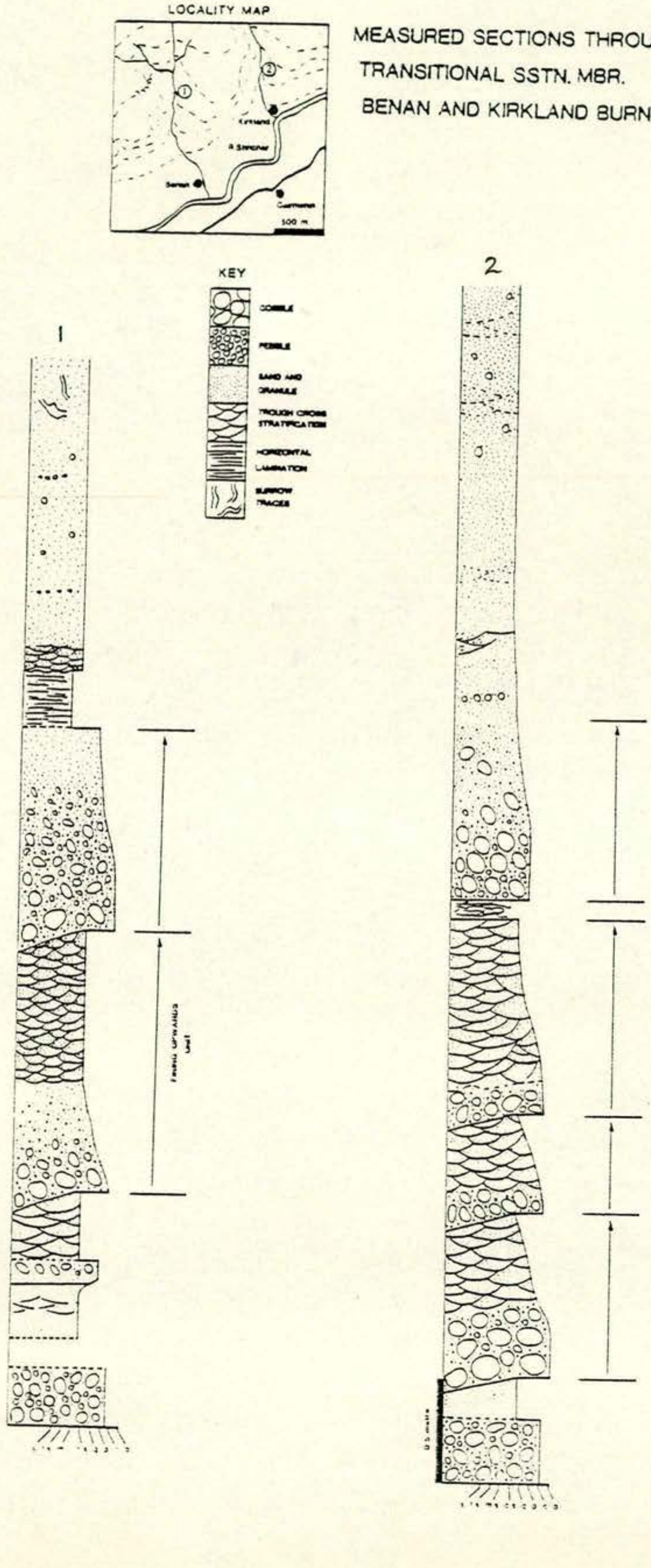
As outlined in Chapter 2, the Transitional Sandstone Member of the Kirkland Formation is laterally equivalent to the Auchensoul Limestone Member and probably the Auchensoul Bridge Mudstone Member, these being described in sections 3.4 and 3.5.

3.2.1 Field Observations

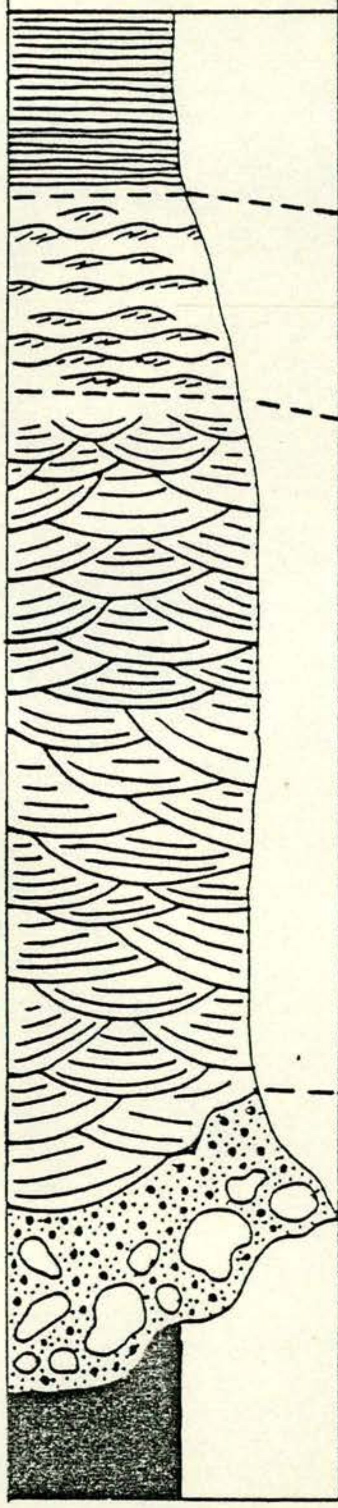
Production of detailed sedimentologic logs is possible only at the Benan and Kirkland Burn localities, Fig. 3:7. A similar sequence, too poorly exposed for accurate measurement, is seen in Kirkdominae Burn, Fig. 3:2. At both localities the conglomeratic Member is directly overlain by a 3-4 metre thick sequence of trough cross-stratified, channelled sandstones and conglomerates. Each measured section consists of a sequence of fining-upwards cycles, each of which may be up to 1 metre in thickness, best developed in the Kirkland exposures. The sequence of depositional events that may occur within a given cycle are summarised in Fig. 3:8. The base to each cycle is conglomeratic, Fig. 3:7 and Plate 3:7, Fig. 1 and moderately erosive, Plate 3:7, Fig. 2. Pebble- to cobble-size detritus is of the same compositional range as seen in the Conglomerate Member. Above the basal horizon a sequence of cross-stratified sands fines upwards to the top of the cycle. The type of cross stratification changes through each unit from medium to small-scale trough-cross-bedding at the base of a cycle to ripple bedding at the top. Horizontal lamination may occur at the very top of a cycle, Plate 3:7, Fig. 3 although infrequently preserved due to downcutting at the base of succeeding unit, Plate 3:7, Fig. 2. Cycles at the top of the Member may show lower amplitude, longer wavelength cross stratification, with only slightly erosive 'ripple' bases towards the top of the unit, Plate 3:7, Fig. 4. The morphology of this type of cross bedding is markedly different from the trough and ripple bedding seen

Figure 3.7

MEASURED SECTIONS THROUGH
TRANSITIONAL SSTN. MBR.
BENAN AND KIRKLAND BURNS



Summary and interpretation of Transitional Sandstone Member fining upwards cycles.



	DESCRIPTION	INTERPRETATION
	Laminated silty fine sand	Deposition of suspension load by fallout from currents of less than ripple velocity.
	Medium to fine sand small scale cross stratification	Deposition as current ripples from low velocity currents (Lower flow regime.)
	Coarse to medium reddened sand Scattered granules and rare pebbles Medium scale trough cross stratification decreasing in magnitude upwards Sands fine upwards from base of unit Possible burrow traces present	Deposition as dunes or mega-ripples migrating within channel Moderate current velocities, decreasing towards top of unit. (Lower flow regime.)
	Granule/pebble/cobble conglomerate Base strongly erosive.	Lag deposit at base of scoured channel floor
	Top of previous cycle	

Plate 3.7

Figure 1.
Erosive pebbly base to fining upward sequence in Transitional Sandstone Member. Faint burrow traces are present at a).
Locality, Benan Burn (NX29,239 925).
Scale is given by pen (11cm).

Figure 2.
Erosive base to fining upwards channel unit in Transitional Sandstone Member marked by irregular pebble horizon. Also shown in the extensive trough cross-stratification.
Locality, Benan Burn, (NX29,239 925).
Scale as shown in photograph.

Figure 3.
Fine grained, silty very fine sand, planar laminated top to fining upwards sequence overlain by cobbly base to overlying channel unit.
Locality, Benan Burn, (NX29,239 925).
Scale is given by pen (11cm).

Figure 4.
Low amplitude cross-stratification and medium sand lens in fine sands and silty very fine sands of topmost part of Transitional Sandstone Member.
Locality, Benan Burn, (NX29,239 925).
Scale is given by pen (11cm).

Plate 3.7

Figure 1

Figure 2

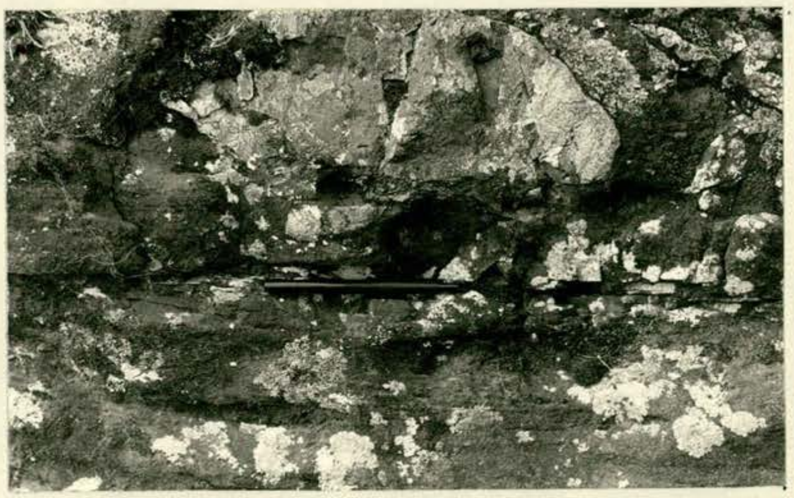


Figure 3

Figure 4

in lower cycles. Occurring as it does in relatively fine sediment this form of bedding may represent hummocky cross-stratification (Harms 1975) (probably synonymous with truncated wave ripple laminae of Campbell, 1966) thought to form as the result of strong wave action generated by storm activity (Harms, 1975, Kumar and Sanders, 1976). This forms in the nearshore or shoreface environment, frequently being developed inshore of an associated facies characterised by biogenic sediment reworking (Clifton, Hunter and Philips, 1971, Kumar and Sanders, 1976). In the transgressive Girvan sequence this facies may be represented by the Benan Burn Sandstone Member that overlies the Transitional Sandstone Member, Section 3.3.

Palaeocurrent data, Fig. 3:9, shows that currents depositing the sandstone member flowed, with little variation, along a roughly N.-S. axis, although it is not possible to determine the actual direction of sediment transport due to the nature of the available exposures. Observed downcutting channels have the same orientation as the troughs.

No macro-fauna has been reported from the member, nor has any been recovered during the present study. Vertical burrows of unknown affinity, Plate 3:7, Fig. 1, occur infrequently, no other ichnofauna was observed.

Core recovered from appropriate levels of the I.G.S. Benan Burn Borehole shows four fining upwards cycles and an unusually thick (0.5m) conglomeratic unit at 155.15m, Plate 3:9. The borehole material confirms the observations made from surface exposures, apart from the obvious difficulty in recognising large scale cross stratification. Representative sections of core are shown in Plates 3:8 and 3:9, with descriptions and interpretation.

The scale of available surface exposures does not allow proper recognition of any large scale channel features.

3.2.2 Petrology

All sandstones within the Transitional Sandstone Member can be classified as lithic arkoses using the scheme proposed by Folk (1968). Angular to sub angular grains of relatively fresh, feldspar (dominantly albite) comprise 30-35% of the grains present. Both single crystal and polycrystalline quartz are present, together amounting to 30-35%. Roundness of the quartz grains tends to be slightly higher than that of either feldspar or lithic grains.

Figure 3.9

TRANSITIONAL SSTN. Mbr. PALAEOCURRENTS

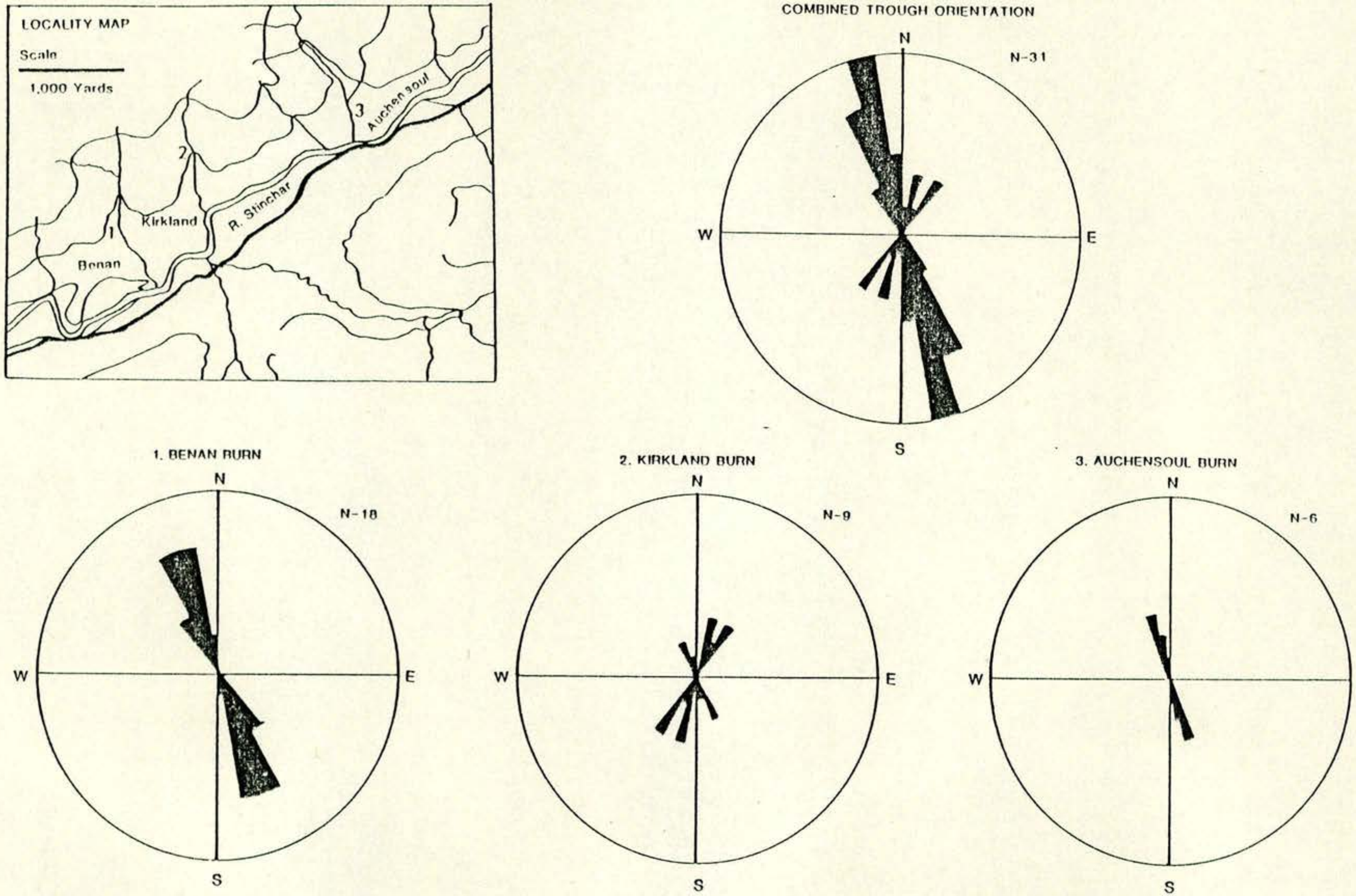


Plate 3.8

Cut surfaces of core through Transitional Sandstone Member, recovered from I.G.S. Benan Turn Borehole.
The core shows the conglomeratic base to a fining upwards unit, underlain and overlain by cross-stratified sands.

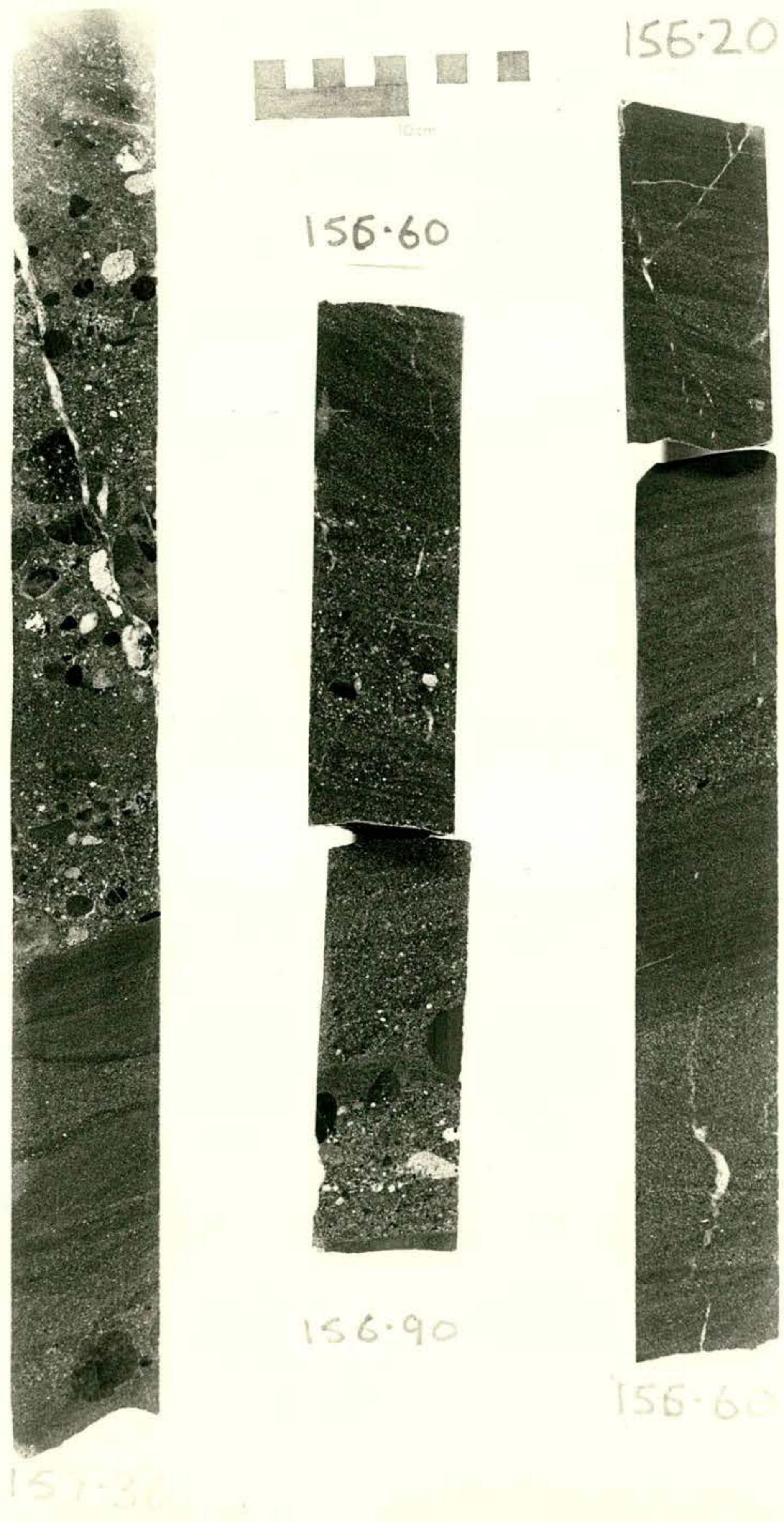
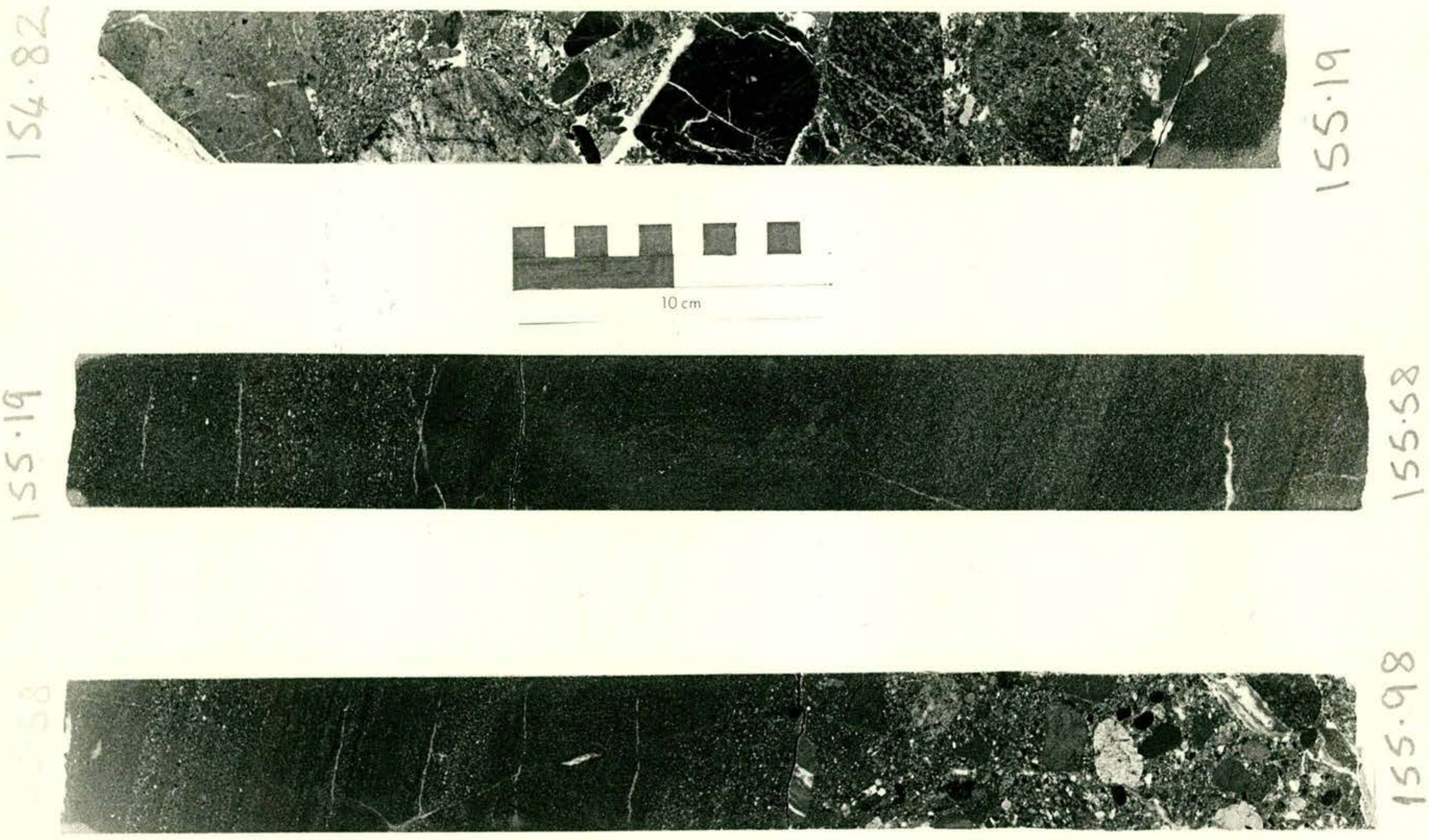

156·20
156·60
156·90
156·60

Plate 3.9

Cut surfaces of core recovered from Transitional Sandstone Member as present in I.G.S. Benan Burn Borehole.

One complete fining upwards sequence and the base of the succeeding are shown.


154·82
155·19
10 cm
155·19
155·58
155·98

Moderately well rounded lithic grains (20-25%) are dominantly of basaltic lithologies, although serpentinitic material is also present as is a small amount of chert. Large aggregates of chlorite and hornblende, probably pseudomorphous after pyroxene, are a minor but distinctive component.

Intergranular areas are filled with cementing clay minerals and minor calcite. Initial crystal growth was usually of clay minerals, calcite forming as a later cement, infilling the residual porosity. Carbonate veins with ill-defined margins are also present, areas cemented by vein calcite are characterised by the complete absence of clay minerals, a floating texture, grains no longer forming a framework, and highly corroded, dentate, grain boundaries, Plate 3:10, Fig. 1.

Opaque minerals, both detrital and authigenic, may form up to 5-7% of the grain population. The detrital opaques have moderately high reflectivity, most having a faint purple hue, possibly indicating either titanomagnetite or ulvo spinel, both of which are consistent with a derivation from the Ballantrae Complex lavas or ultrabasics. Concentrations of opaque minerals as lag deposits on the laminae of cross stratified units may occur. Pyrite is the sole euhedral authigenic opaque mineral present.

Texturally and mineralogically the sandstone are submature to immature, this precluding prolonged attrition in beach or intertidal environments. Haematite staining of quartz and feldspar grains is common, occurring at grain margins and along fractures within the grains, Plate 3:10, Fig. 4. (Walker, 1967) describes closely comparable features from Recent and Pliocene fanglomerates and associated sediments. Reddening is attributed to the diagenetic formation of haematite and associated clay minerals as a result of the breakdown of ferromagnesian minerals, particularly hornblende and biotite (compare Plate 3:10, Figs. 2 and 3 with Plate 1, Fig. 2 of Walker (1967). Results confirming the diagenetic origin of reddening in many sediments are reported by Walker (1974). A similar, diagenetic origin is proposed for the reddening seen in the Kirkland Formation sandstones.

3.2.3 Discussion and Interpretation

Fining upwards cycles and lack of marine fauna have been interpreted as indicative of a fluviatile environment for sandstones

Plate 3.10

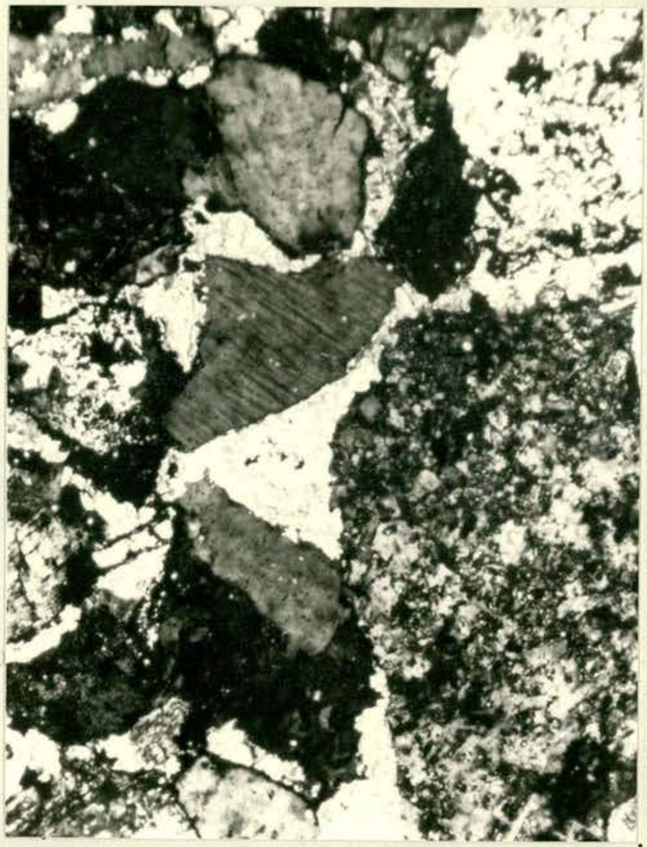
Figure 1.
Dentate margins to quartz, feldspar and lithic grains in carbonate cemented sandstone.
Thin section, BBH/8/80, plane polarised light.

Figure 2.
Remnant of hornblende crystal grain (H) surrounded by opaque aggregates of haematite cement and haematite stained detrital grains.
Thin section, BBH/8/80, plane polarised light.

Figure 3.
Extensive replacement of detritial hornblende by chlorite/illite aggregate - opaque haematite is abundant around the former grain.
Thin section, BBH/8/80, plane polarised light.

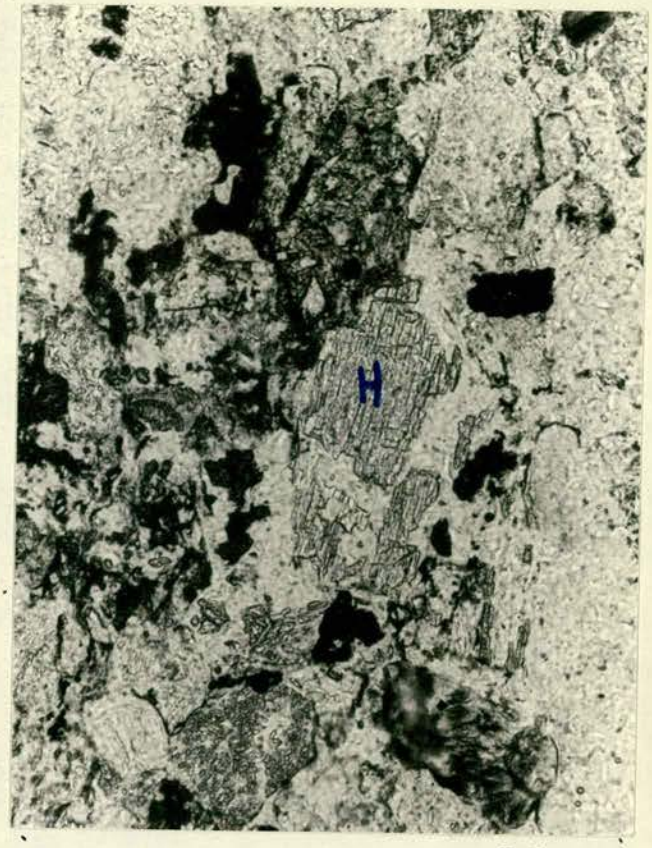
Figure 4.
Haematite occurring along cleavage planes within large, altered feldspar grain.
Thin section, BBH/8/80, plane polarised light.

Plate 3.10



0.1mm

Figure 1



0.1mm

Figure 2

Figure 3

0.1mm

Figure 4

0.1mm

of Jurassic age in E. Greenland (Sykes, 1974). This interpretation is strengthened by the presence of plant debris and poorly developed coals. Similar sequences to those described by Sykes have been reported from the Upper Coal Measures of South Wales by Kelling (1968). The major work on fining upwards cycles has, however, been carried out during research into Old Red Sandstone fluviatile deposits of the Anglo-Welsh area (Allen, 1964, 1965). From these studies Allen concluded that in general fining upwards sequences result from deposition by lateral accretion on point bars in sinuous fluvial systems, Allen (1970).

In the case of the Transitional Sandstone Member no evidence for a fluvial environment, other than the fining upwards cycles, are seen. Indeed the laterally equivalent Auchensoul Limestone Member is of shallow marine origin (see Section 3.4).

Two interpretations of the Transitional Sandstone Member can be made, either of which is consistent with a picture both of fan delta development and of a probably shallow marine environment.

Deltas, of which fan deltas can be considered a coarser grained variant type, can be classified in terms of the dominant process responsible for determining the delta morphology. Galloway (1975) recognises three main types of present day deltas, using a ternary diagram, Fig. 3:10, according to the relative importance of fluvial, wave or tidal processes.

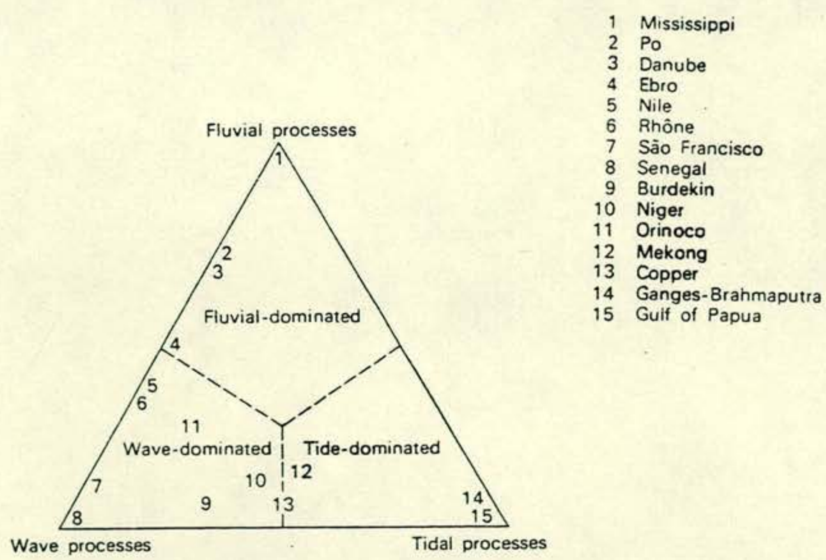


Figure 3:10 Ternary diagram of delta types, modified after Galloway (1975) by Reading (1978).

In wave or tide dominated deltas such as the Senegal (wave dominated) or Ganges-Brahmaputra (tidal dominated) the distribution of sediment and the structures resultant from redistribution of sediment, reflect the process responsible, rather than the fluvial process which transported sediment to its original site of deposition (Collinson et al., 1978, Wright, 1977). Thus, according to one interpretation, as there is evidence indicative both of a marine environment and typically fluvial processes, deposition may have taken place in a fluvial dominated sub-aqueous delta/fan delta setting.

Furthermore, the preservation of structures and sequences thought to be indicative of fluvial processes, suggests a low energy (low wave energy, microtidal) environment. The distribution of Barr Group sediments indicates that they were deposited on a narrow shelf (Williams, 1962). As there is a positive correlation between shelf width and tidal range on present day coastlines (Cram, 1979), it is probable that microtidal conditions prevailed in the Girvan area during the Middle Ordovician.

The extent of subaerial exposure on the delta top cannot be evaluated in the field due to the small scale, isolated nature of the exposures available. Nowhere are there any indications of subaerial exposure, such as mudcracks or similar structures, caliches or coals, although this is not proof that exposure did not occur.

Presend day delta tops may be divided into three broad sub-environments; (i) distributary channels, bounded and constrained by (ii) levees. The areas between distributary channels are termed (iii) interdistributary bays (Coleman et al., 1964). These may be freshwater, brackish or marine (Elliot, 1974). These terms can also be applied to the delta plain. Minor environments present may include crevasse channels, crevasse splays and minor mouthbars. Elliot (1974) interprets fining upwards sequences in the Rhone delta as either crevasse channel (units <1m) or distributary channel (>1m) deposits.

The Transitional Sandstone Member sequences seen in Benan and Kirkland Burns are probably best interpreted as distributary channel deposits. The scale of individual fining-upward units, the near unidirectional palaeocurrents and the vertical repetition of these units is inconsistent with a crevasse channel interpretation. Although there is insufficient data to be able to comment on stream morphology it is worth noting the similarity of the Transitional Sandstone Member cycles to those described by Sykes (1974) from the Jurassic of Greenland and by Elliot (1975) from the Carboniferous delta systems of northern England. Sykes utilised the low sinuosity/low braiding model proposed by Moody-Stuart (1966) for fluviatile fining-upwards sequences lacking the epsilon cross stratification (Allen, 1963), now thought to be indicative of laterally accreting point bars in meandering, high sinuosity rivers (Allen, 1965). The model proposed by Moody-Stuart (1966) based on Nedeco (1959) and Chien (1961) invokes a sinuous talweg (Appendix I) meandering between near straight high stage banks. Allen (1970) concludes, "The possession of a sinuous talweg, if not a sinuous high stage channel seems to be an essential feature of all streams, and lateral deposition is the dominant process of bar movement whenever such sinuosities of channel <u>or</u> talweg occur." Scouring of the channel floor, producing lag concentrations of gravel may occur, as suggested by Leopold Wolman and Miller (1964). In summary, deposition of Transitional Sandstone Member sediments may have taken place in a distributary channel on the distal, subaqueous part of a fan delta. Fining upwards sequences in the member are tentatively attributed to lateral deposition on bars produced by a sinuous talweg migrating within the relatively straight sides channel of a deltaic distributary, which built out into a marine environment.

The second, alternative, interpretation of the Transitional Sandstone Member sequences is as follows. Deposition may have occurred in tidal channels dominated by strong ebbtide currents or storm generated currents as suggested by Dreise et al. (1981), for trough cross stratified units in the Mt Simon Formation of Wisconsin. Ebb tide dominated deltaic channels have been interpreted as responsible for producing unidirectional trough cross stratification and fining upwards cycles (Johnson, 1975, Brenchley and Newall, 1980, Watchorn, 1980). In the sequence described by Johnson the 3m thick fining upwards unit has a conglomeratic, lag deposit base, but there is no repetition of the unit, such as is seen in the Kirkland Formation sequences. The repitition of cycles indicates successive addition of new, coarse grained, sediment that cannot sensibly be explained in terms of a tidal channel where little

Plate 3.11

Cut surfaces of core through lower part of Benan Burn Sandstone Member as recovered from I.G.S. Benan Burn Borehole. Numerous granule and small pebble horizons are present, showing a variety of sedimentary structures, from planar lamination (151.74m) to steep cross-stratification (149.59m). In the latter instance the unit from 149.62m - 149.54m has been deposited as a single event, probably from a decelerating storm surge or effluent flood current.

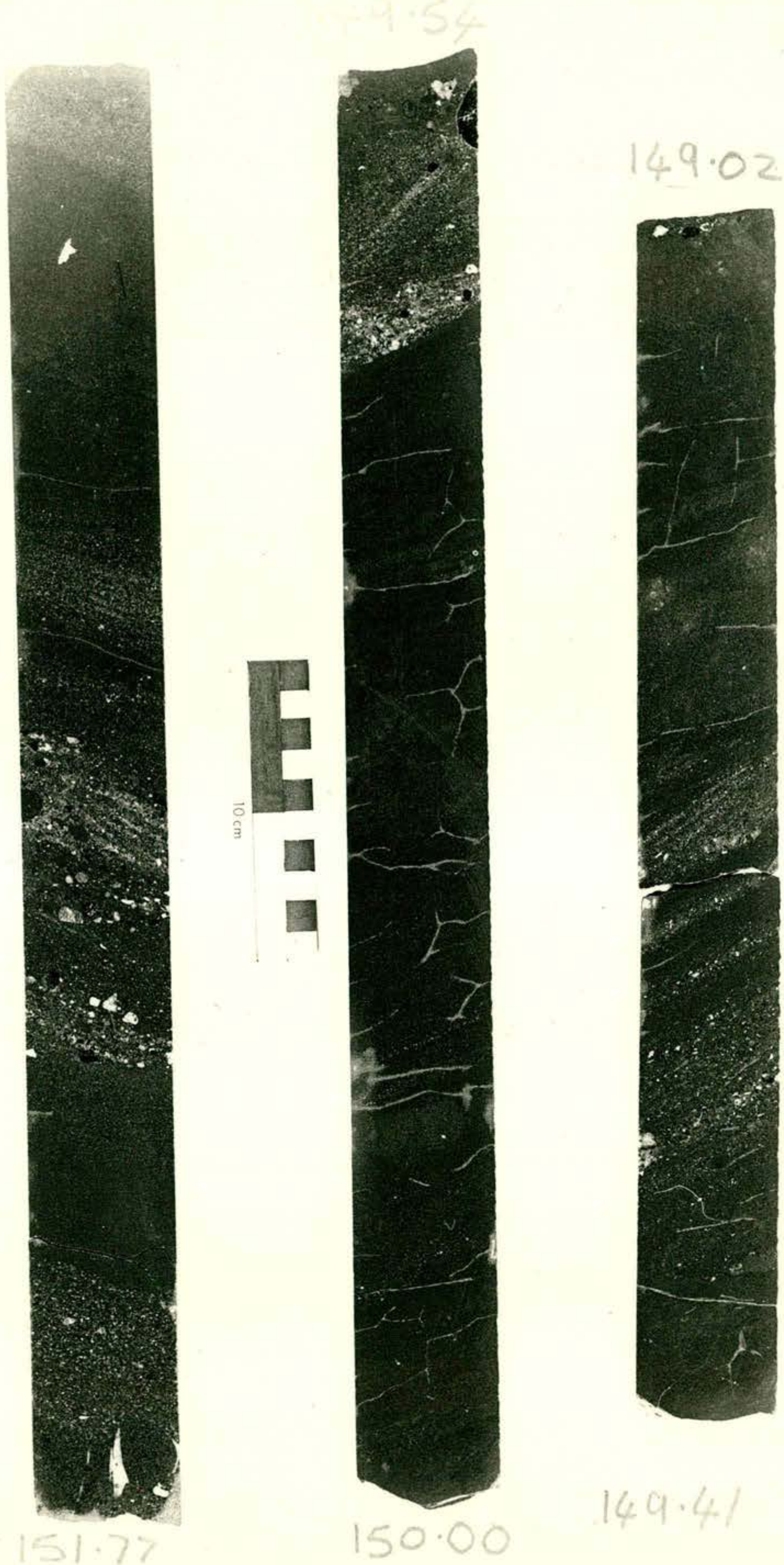

9·54
149·02
10 cm
151·77
150·00
149·41

Plate 3.12

Cut surface of core through Benan Burn Sandstone Member as seen in I.G.S. Benan Burn Borehole. Note the presence of erosively based pebble horizons, faint cross-stratification (148.97m) and faint diagenetic mottling due to localized carbonate cementation (145.43m).

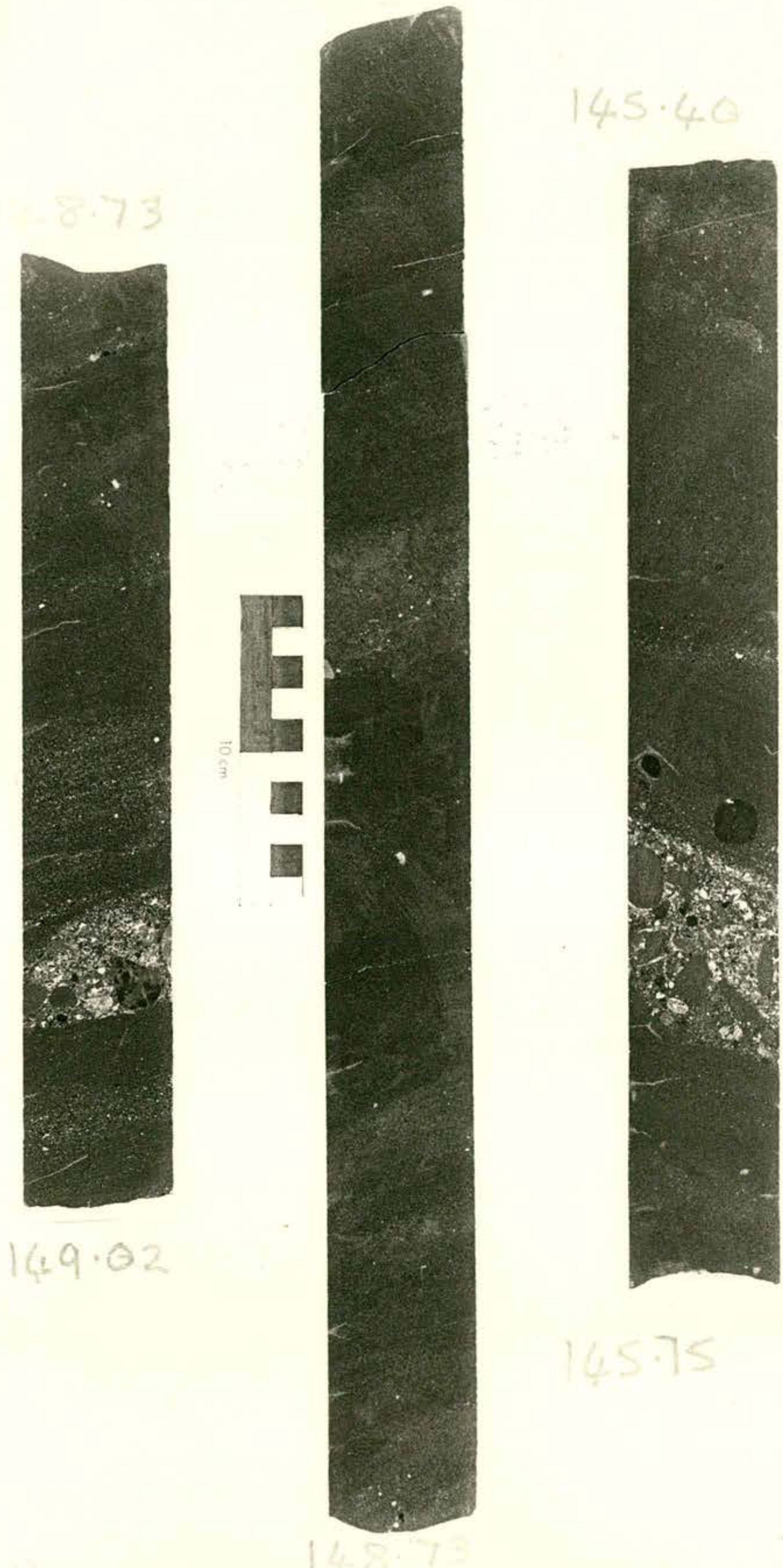
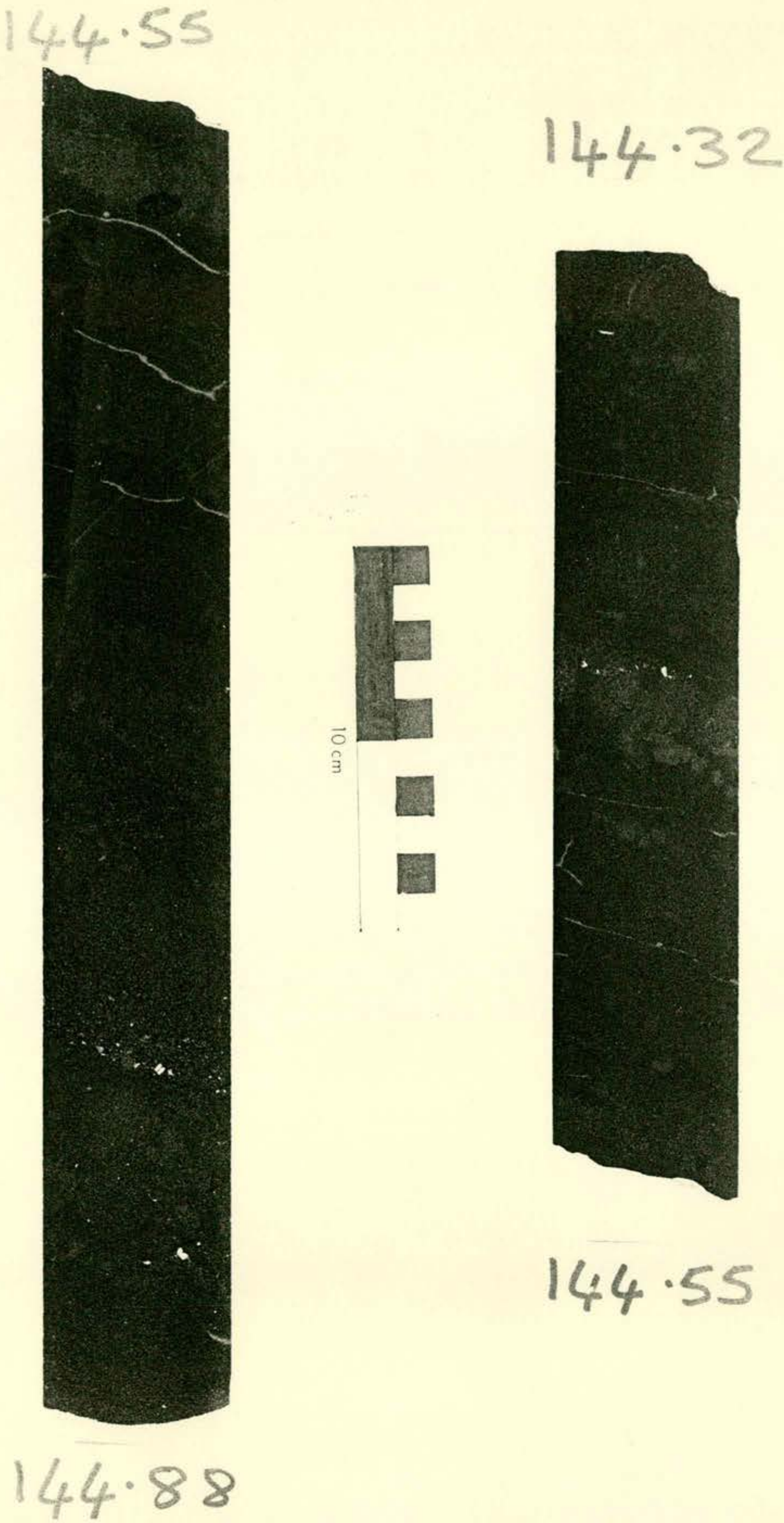

145·40
8·73
10 cm
149·02
145·75
148·73

Plate 3.13

Cut surfaces of core from middle part of Benan Burn Sandstone Member as seen in the I.G.S. Benan Burn Borehole. The sediments are in general thoroughly bioturbated, although bedding may be marked by thin accumulations of bioclastic debris (e.g. 144.78m).


144·55
144·32
10 cm
144·55
144·88

sediment input occurs from a generally inactive or non existent fluvial sediment supply unless repeated channel migration and continual subsidence has taken place. Such a process would, however, produce horizontal gravel lags, rather than the clearly channelized conglomerates of the Member. For this reason the first interpretation is preferred, although it must be admitted that the basis for this is somewhat scanty in terms of indisputable facts.

3.3 Benan Burn Sandstone Member

3.3.1 Introduction

The Transitional Sandstone fines upwards into the Benan Burn Sandstone Member, a sequence of medium to fine silty sands (onfinis lags of previous authors). It is in this unit that the first definite evidence for a fully marine environment is seen in the type sections. Grain size decreases upwards, and gradually, with increased carbonate content, the member passes upwards into the Stinchar Limestone Formation.

Exposures are generally of poor quality, particularly in the upper part of the unit, which is prone to decalcification. The lower part of the unit is best exposed in Benan and Kirkland burns, whilst exposures near the disused limekiln at Minuntion (NX29 2200 9110) clearly show the passage into the Stinchar Limestone Formation. The only complete section through the unit is provided by the I.G.S. Benan Burn Borehole. Plates 3:11, 3:12, 3:13 show representative sections of the core material.

3.3.2 Sedimentology and environmental interpretation

The member displays few features that unequivocally indicate a distinctive sedimentary environment. For the most part the unit comprises variably bioturbated, silty, medium to fine sands. Reddening of the sands is more apparent in the lower part of the sequence, being replaced by a greenish colouration towards the top. Thin bands of generally well rounded, high sphericity pebbles (Plate 3:14, Figs. 1-4) (pebble trains) occur throughout the unit. The pebble trains may also contain rip-up clasts, Plate 3:14, Fig. 1, well-rounded clasts of fine, faintly laminated sand. Bioclastic material may be concentrated within the pebble train itself or in the 3-5cm thick rippled unit that in general overlies

Plate 3.14

Figure 1.
Erosively based pebble train consisting largely of rip-up clasts, with bioclastic debris also abundant.
Core surface, 145.65m, Benan Burn Borehole.
Scale is graduated in centimetres.

Figure 2.
Thin pebble train overlain by thick steeply cross-stratified coarse sand unit, the whole deposited as a single event.
Core surface, 146.16m, Benan Burn Borehole.

Figure 3.
Thick erosively based pebble unit overlain by relatively thin cross-stratified unit.
Core surface, 146.92m, Benan Burn Borehole.

Figure 4.
Pebble train unit showing upwards penetration of substrate sediment into intergranular voids.
Core surface, 147.61m, Benan Burn Borehole.

Plate 3.14

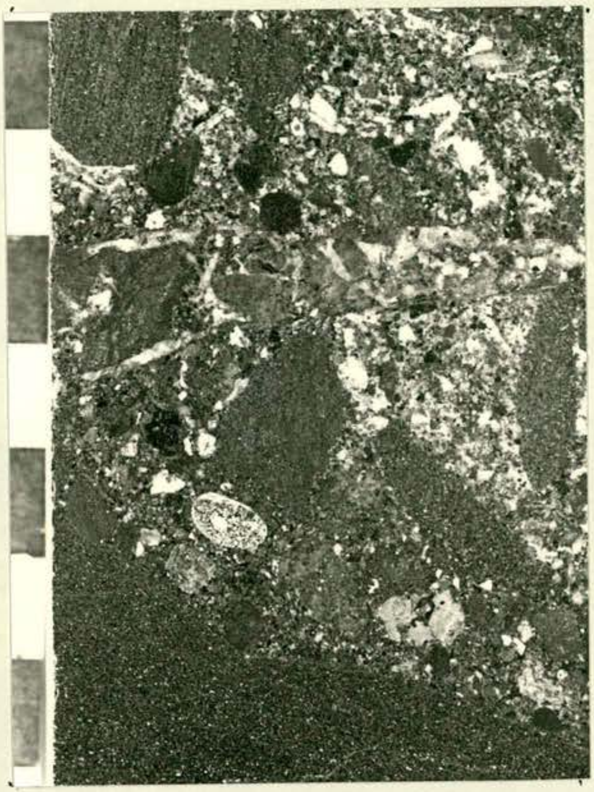


Figure 1

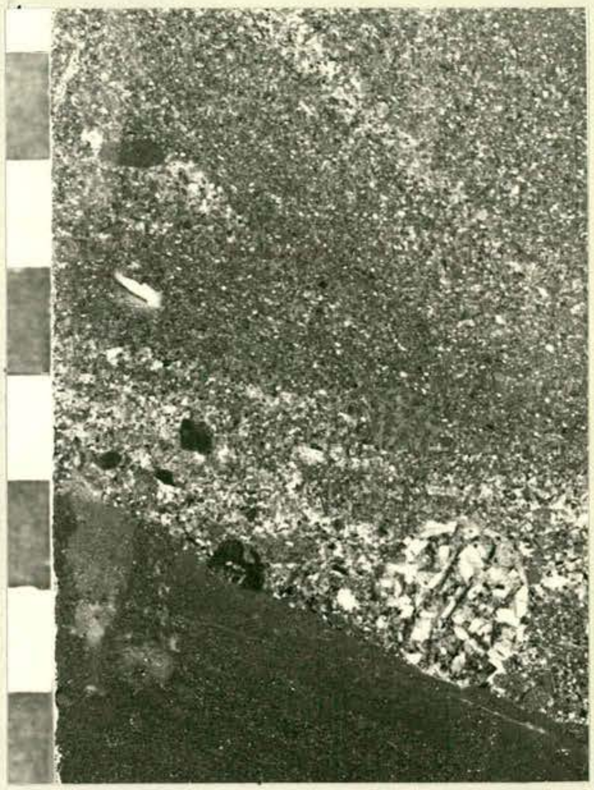


Figure 2

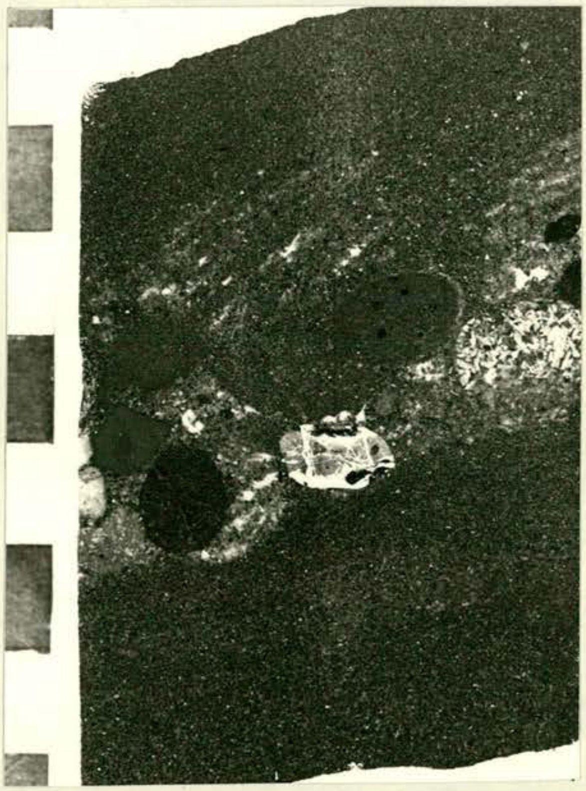


Figure 3

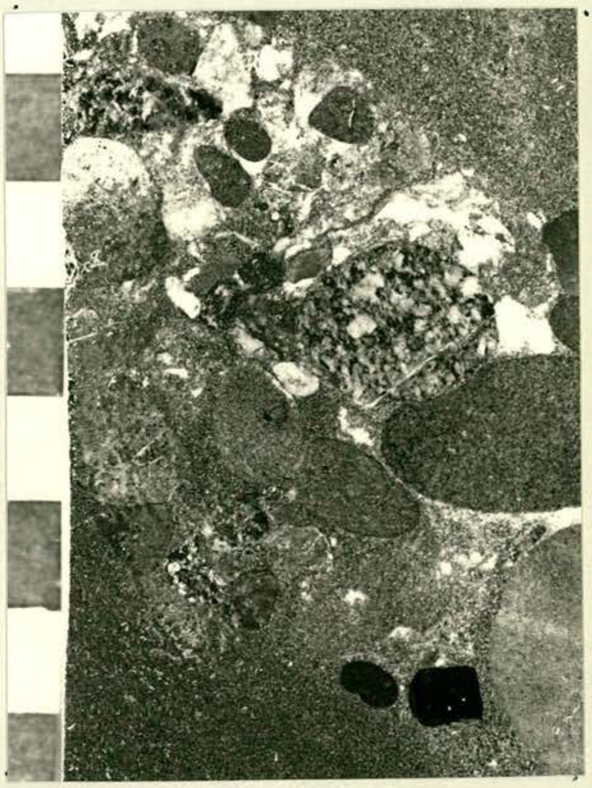


Figure 4

the pebble band, Plate 3:14, Figs. 2 and 3. Bases to pebble trains are variable and although generally sharp may be diffuse in some cases possibly showing signs of upward flowage of wet sediment as a result of loading by the pebble band (Plate 3:14, Fig. 4). Between these two extremes a complete gradation of base character exists.

Sheet sandstones, essentially the same as those more readily observed in the Stinchar Limestone Formation, appear in the upper part of the Member, where they are noticeably less heavily bioturbated than the surrounding sediment. Such sand bodies have not been recognised in the field, only having been recorded in core sections, therefore no impression of sand-body morphology can be gained. In all observable aspects these sandstones conform with sheet sandstones as described by Goldring and Bridges (1973).

No primary sedimentary structures indicative of sediment reworking by either tidal or wave currents are seen in the Member. As possible hummocky cross-stratification occurs at the top of the Transitional Sandstone Member it is reasonable to suggest that the Benan Burn Sandstone Member represents shallow sub-tidal sedimentation, deposition occurring below both normal and storm wave base.

As already mentioned the unit fines and becomes more calcareous towards the top. Pelmatozoan debris is the dominant bioclastic grain type seen in the lower part of the unit. Calcareous algae, particularly the probable cyanophyte Girvanella and the possible codiacean Nuia, become increasingly more important through the Member. Valcourea confinis dominates the brachiopod fauna, occurring in general as well sorted bands of disarticulated valves, articulated specimens being seen only rarely. The shelly fauna of the member is locally both abundant and diverse, 24 species of brachiopod (Williams, 1962) 32 species of trilobite (Tripp, 1962) and one of the few recorded British species of L.-M. Ordovician crinoids (Ramsbottom, 1961), having been recovered from localities at Minuntion and Kirkdominae. Comparison of the trilobite fauna with those described from the Arenigian of Spitzbergen by Fortey (1974) and thought to represent a number of depth related communities, indicates that representatives of the shallowest, Illaenid/Chaerurid, community are present (see Section 4.7). Genera assigned to the deeper water, Nileid, community by Fortey are however also present.

Bioturbation is thorough, except in the case of sheet sandstones, where only the top few centimetres are biologically reworked. Both horizontal and vertical burrows are present, picked out by heavily-reddened mud either filling or lining the burrows, and may also be distinguished by both upwards and downwards mixing of coarser or finer, or more or less calcareous, sediment.

The Benan Burn Sandstone Member is considered to be a shallow, subtidal deposit. In general, deposition was relatively slow, with little or no physical reworking of sediment taking place. Bioturbation only affected the top few centimetres below the sediment surface, as shown by the minimal burrowing of the sheet sandstones. The presence of fine-grained detritus probably indicates deposition from medium to low velocity currents and also perhaps from suspension, combined with a lack of reworking by strong currents. Sheet sandstones may be the result of either remobilization of sediment from the beach zone during storm events or deposition from turbidity currents initiated by sediment laden effluent floods, as suggested by Goldring and Bridges (1973). Pebble trains are thought to be the product of medium to high velocity effluent discharges, probably lacking in sediment content resulting from periodic flood events. The variety of bases to pebble trains reflects a similar variety of substrates consistency in the underlying sediment.

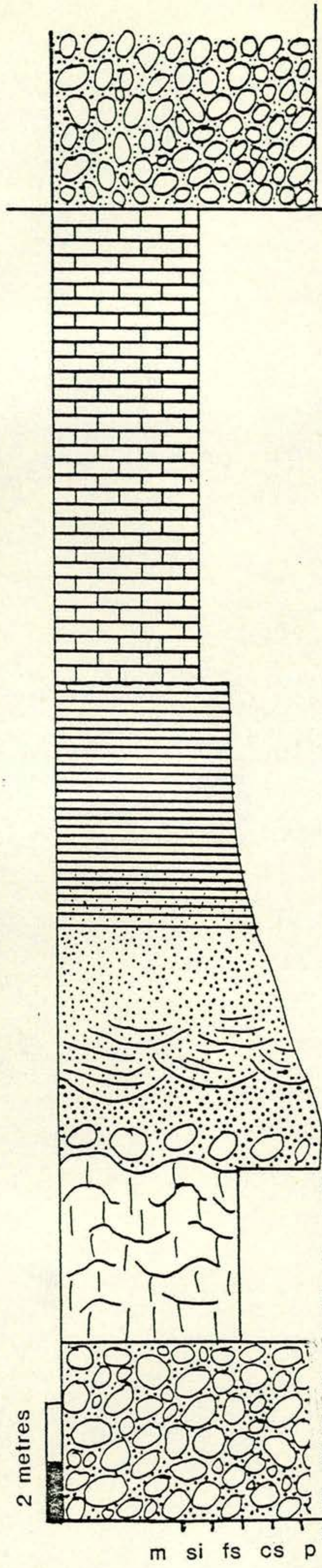
3.4 Auchensoul Limestone Member

3.4.1 Introduction

Thin developments of impure carbonates assigned to the above unit outcrop at the localities noted in Chapter 2. The dominant lithology at all outcrops is a variably reddened silty or sandy algal/foraminiferal limestone. In the type section of Auchensoul Burn the limestone directly overlies the conglomeratic member and is in turn overlain by cross stratified sands of the Transitional Sandstone Member, Plate 3:15, Fig. 1 and Fig. 3:11. Elsewhere the stratigraphic position of the unit is either slightly different to that seen in the type section or cannot be accurately placed or is not developed. In exposures around the Struil Well (NX29 2510 9295)

Measured section, Auchensoul Burn

Figure 3.11



Benan Fm. Conglomerate Mbr: Polymict, matrix rich, sometimes clast supported. Clasts of Stinchar Lst. Fm. lithologies abundant at base of section, basaltic clasts are common. Rare clasts of greyish red limestone, resembling Auchensoul Limestone Member litholgies. Matrix of coarse sand with granules.

Stinchar Limestone Formation: Medium grey, impure algal limestone alternating with more clay rich horizons. Thinly bedded (3-4 cm.). Algal growths frequently concentrated at the bases of limestone bedded units.

Benan Burn Sandstone Member: Greenish black calcareous siltsone with occasional clasts of coarser detrital material present at restricted horizons. Disarticulated brachiopods locally common, burrow traces present.

Transitional Sandstone Member: Medium grey calcareous sandstone, cobbles and pebbles of basic igneous material concentrated at base of unit. Trough cross stratification well developed. Unit fines upwards and is gradational into the overlying silt stones.

Auchensoul Limestone Member: Light brownigh grey limestone. Abundant algal material present, locally very pure with sutured seam stylolites. Detrital material up to granule size present. Top of unit irregular.

Kirkland Fm. Conglomerate Mbr: Polymict, matrix rich unstratified Clasts moderately well rounded, dominantly basic and ultra-basic igneous with some chert. Matrix of coarse sand with granules, compositionally similar to the clast assemblage.

Plate 3.15

Figure 1.

Junction between Auchensoul Limestone Formation, below hammer, and thin Transitional Sandstone Member sequence above. The junction is irregular and is marked by a thin gravel horizon. The medium/coarse sands of the Transitional Sandstone Member are trough cross-stratified. Locality, Auchensoul Burn, (NX29,262 931).
Scale is given by hammer handle (30cm).

Figure 2.

The encrusting foraminiferid Wetheredella intergrown with poorly defined filaments of Girvanella in Auchensoul Limestone Member, Auchensoul Burn.
Thin section, AUB/1/79, plane polarised light.

Figure 3.

Fenestral fabric developed in dense algal boundstone, with large cavities, possibly of burrow origin, also present.
Thin section, AUR/1/79A, plane polarised light.

Plate 3.15

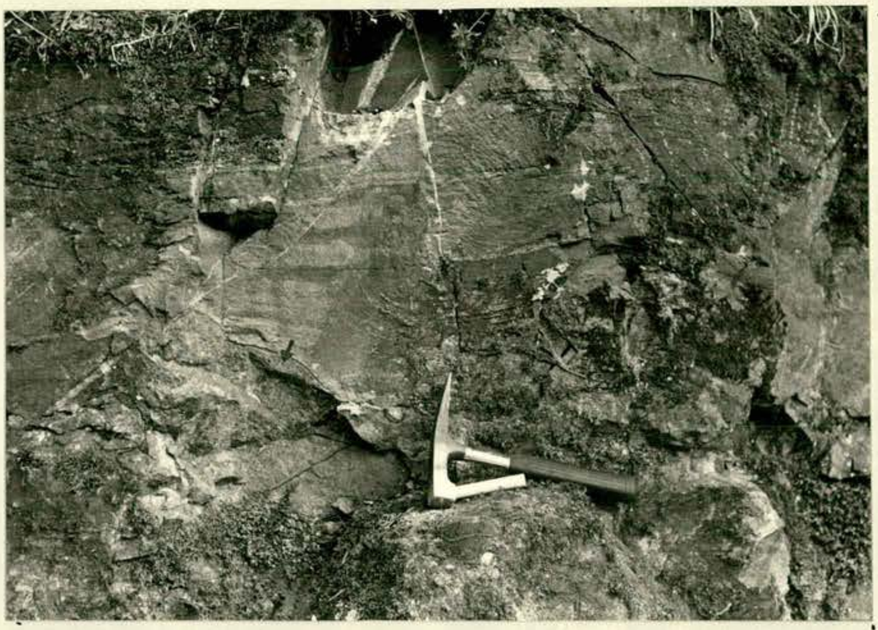


Figure 1

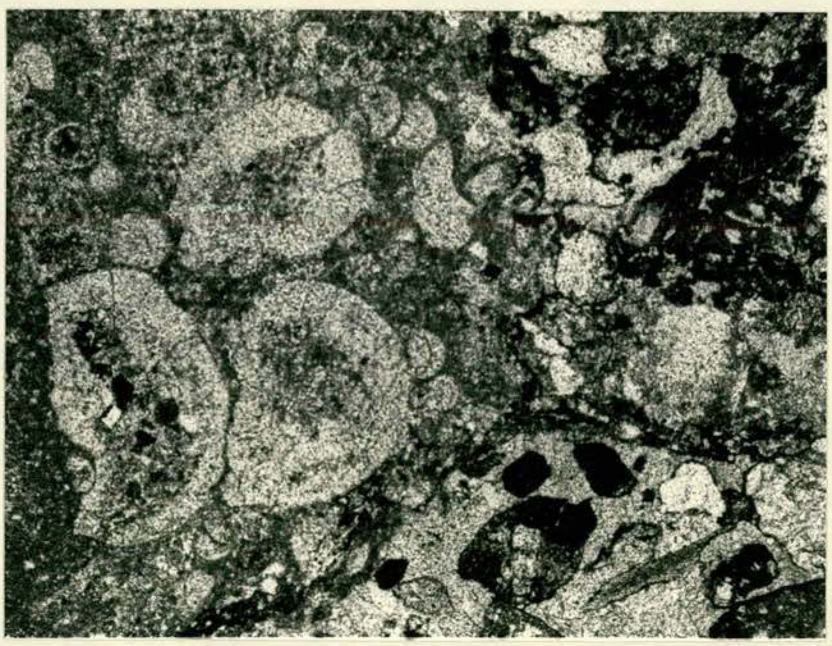


Figure 2

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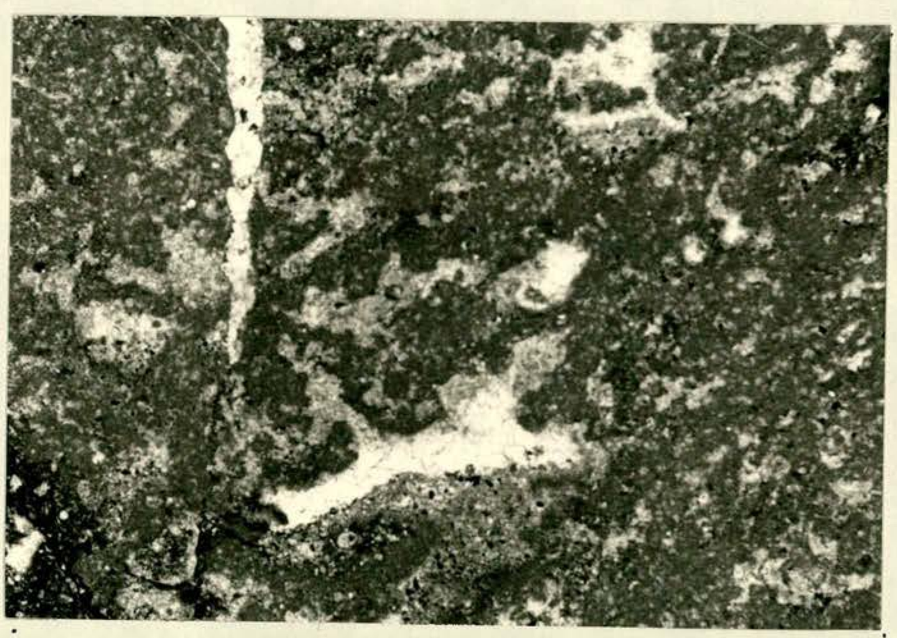


Figure 3

1.25mm

the unit appears to be laterally equivalent to the Benan Burn Sandstone Member (Fig. 2:2, and Williams, 1962). In the bed of the R. Stinchar the unit is separated from the top of the Conglomerate Member by a sequence of muddy, stilty fine sands. At exposures in an abandoned quarry on Doularg Hill (NX29 2650 9245) no stratigraphic position can be determined for the unit, although the geographical position might indicate that these exposures may occur in a sequence usually assigned to the Traboyack Formation, developed S. of the Stinchar Valley, rather than the succession typical of the Barr Group as seen in the type sections. The unit contains a sparse shelly fauna, Ingham (1978).

3.4.2 Sedimentology

Auchensoul Burn and Struil Well

Reddened silty algal limestones outcrop at both these localities. In both cases, laminar, poorly preserved growths of Girvanella are the dominant organic component, in places forming up to 70% of rock volume. Wetheredella, Plate 3:15, Fig. 2 and Nuia also occur, the former as encrustations on and intergrowths with the Girvanella growths, the latter as isolated grains apparently unattached to any substrate. Coarser grained material, fine to medium sand, is present, infilling numerous burrows. In general though the sediment surrounding the algal growths is fine grained. In the Auchensoul Burn section the unit can be seen to decrease in thickness laterally, passing into apparently structureless, calcareous sands. The top of the unit is irregular and is marked by a horizon of cobbles and pebbles, Plate 3:15, Fig. 1, passing upwards into cross stratified sands, Plate 3:15, Fig. 1. Exposures at Struil Well are extremely limited in extent and no more can be said than that as far as can be determined the lithology is essentially the same as at Auchensoul Burn.

Exposures on Craigbickerae Hill mapped by Williams (1962) as Auchensoul Limestone are no longer available, but their occurrence, separated as they are from the main development of the Member, further demonstrates the sporadic isolated nature of the unit.

Since the Auchensoul Limestone Member is a closely juxtaposed lateral equivalent of the Transitional Sandstone Member its environmental interpretation must be related to that of the sandstones, already interpreted as deltaic distributary channel deposits. It is suggested that the limestones at these localities accumulated in the quiet, shallow-water, sediment-starved (relative to the channel areas) environment of a deltaic interdistributary bay. In the Auchensoul Burn section the occurrence of a pebble-cobble horizon above the limestone is taken to represent breaching of a channel wall, with resultant influx of coarse grained sediment into the bay area. Such features are commonplace in the deltaic environment, breaching resulting from high energy, extreme flood events (Elliot, 1974). Similar bays, which may be either freshwater, marine or brackish (Elliot, 1974) have been reported from Pliocene fan deltas of the Appenine region by Ricci - Lucchi et al. (1981).

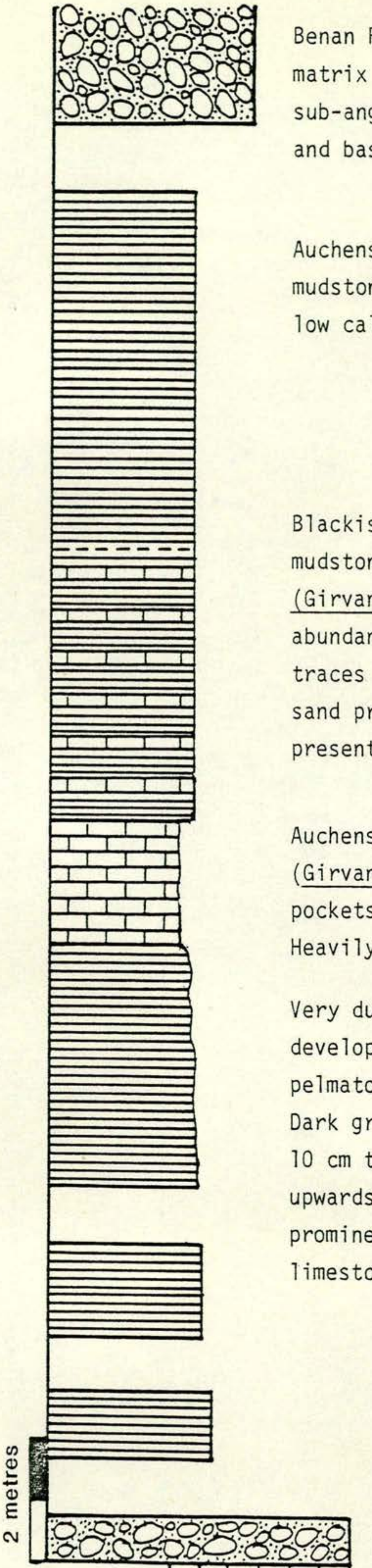
River Stinchar section

A number of carbonate horizons occur in the bed of the R. Stinchar above the bridge of Auchensoul Farm. Of these, only the thickest and stratigraphically lowest horizon bears any resemblance to the Auchensoul Limestone Member as developed in the type section. The remaining carbonate horizons are assigned to the Auchensoul Mudstone Member, Section 3.5.

The horizon in question is separated from the top of the Conglomerate Member by approximately 16.5m of reddened, muddy siltstones with thin developments of medium sandstones, these being assigned to the mudstone member. The limestone horizon itself is approximately 2m thick. Laminar or upright, digitate non transported algal (Girvanella) growths up to 2cm in size, preserved as dense cream coloured calcite are readily recognisable in hand specimen, enclosed by reddened mudstone and are best developed at the top of the unit, Plate 3:16.

Locally the Girvanella growths may develop a texture best described as fenestral, Plate 3:15, Fig. 3 (although no genetic implication is intended). In such areas the algal filaments are less tightly intertwined, more flocculent than in the laminar or digitate growths. Basal parts of the unit are more coarse grained, the less abundant algal growths being surrounded by a sandy matrix, Plate 3:16. Girvanella dominates the algal flora, Nuia, Sphaerocodium, and the foraminiferid Wetheredella are also present. With the exception of non-encrusting foraminiferids, either Saccaminopsis or Thuraminoides, Plate 3:16, virtually no

Measured section, R. Stinchar above Auchensoul Bridge



Benan Fm. Conglomerate Mbr; Pebble-cobble conglomerate, matrix rich, polymict. Abundant clasts of angular to sub-angular Stinchar limestone. Matrix of chert, quartz and basic igneous, sand to granule size fragments.

Auchensoul Bridge Mudstone Member: lackish red silty mudstones, lacking bioclastic horizons low calcareous content. Heavily bioturbated.

Blackish red and dark greenish grey calcarous mudstones with pebbly and bioclastic horizons. Algal (Girvanella) rich areas present. Solenopora fragments abundant at one horizon. Heavily bioturbated, burrow traces abundant. Blebs of dark greenish grey fine sand present in lower part. Pale calcareous blebs present in upper part.

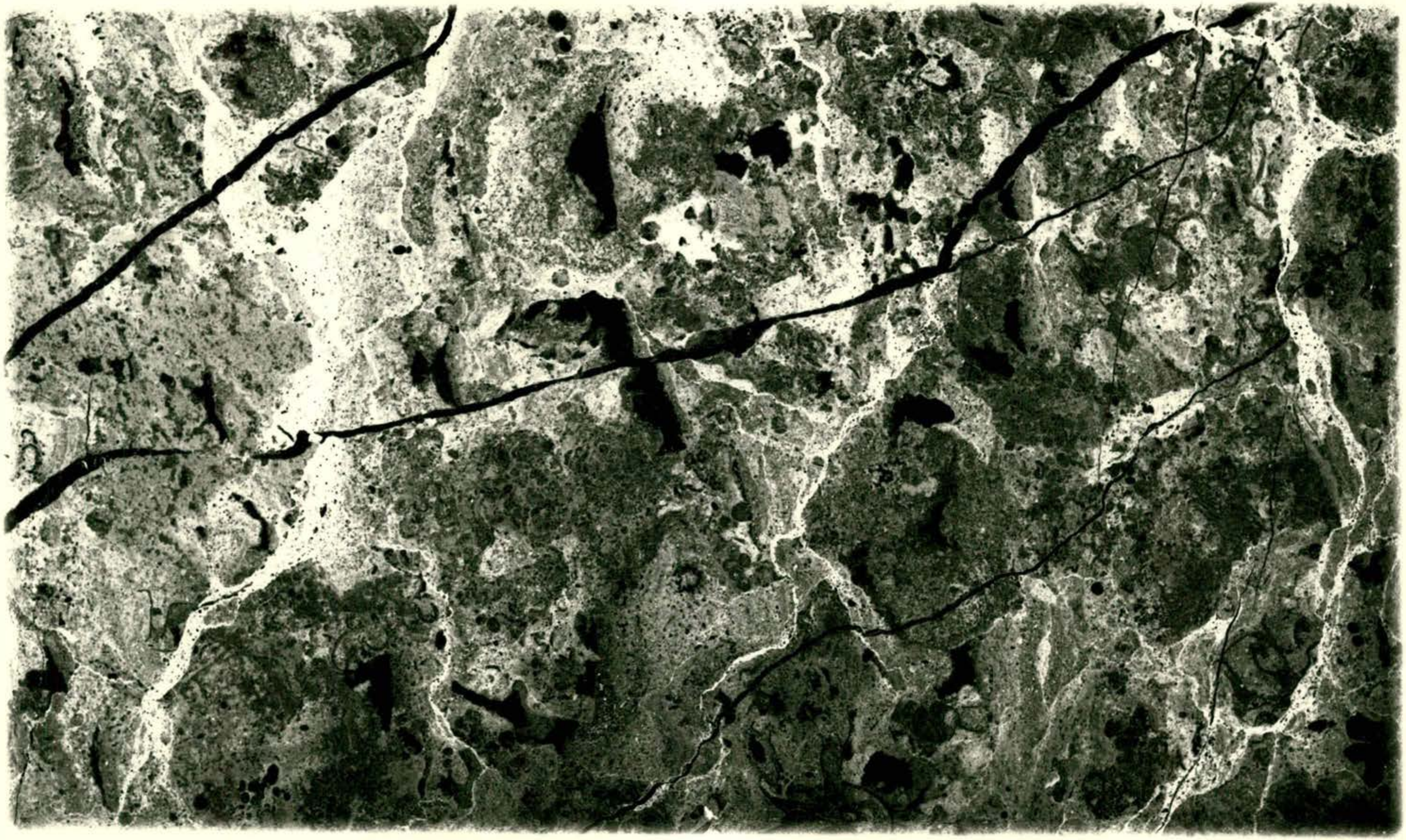
Auchensoul Limestone Member: Greyish red algal (Girvanella) limestone with reddish brown mudstone pockets. Only fine detrital material present. Heavily stylolitised with clay seam formation.

Very dusky red calcareous silty mudstones, poorly developed bedding. Fine grained bioclastic, algal and pelmatozoan material present in small quantities. Dark greenish grey sandy silt horizons present, up to 10 cm thick. Silstones increase in carbonate content upwards. Bioturbation and burrow traces, become more prominent upwards. Transitional into the overlying limestone.

Kirkland Fm. Conglomerate Mbr: coarse, matrix rich rudite. Basic and U-basic clasts with rare granitoids. Greenish black matrix of sand and granule-sized material

Plate 3.16

Negative print of thin section, showing typical fabric of limestones in the Auchensoul Limestone Member as developed in the River Stinchar section. Foraminiferids, Saccaminopsis and Thuraminoides are moderately abundant. The bulk of the section consists of argillaceous algal boundstone cut by numerous non-sutured seam stylolites. Thin section, AUR/1/80.



other faunal or floral element is important within the limestone. Occasional comminuted shell material is seen but is not volumetrically important.

Further evidence of biological activity is provided by the presence of a complex, open, burrow system, developed in the sediment surrounding the algal growths, Plate 3:16. The burrows are not compacted and are infilled geopetally by peloidal silts; in certain cavities well formed peloids can be seen to rest upon the planar surfaces of the geopetal silts, Plate 3:17, Fig. 1. Cavity roofs may be colonised by non-filamentous, coccoid algae, probably best assigned to the genus Epiphyton (Plate 3:17, Fig. 1). The open, non-compacted nature of the burrow systems indicates a cohesive, firm substrate; shelter and possibly sediment stabilisation was afforded by the abundant algal growths. Epiphyton has been described from Middle Ordovician and Cambrian reef environments by Kobluk (1980, 1981, 1981) and Kobluk and James (1979), where it occurs as a cavity dwelling (coelobiontic) organism, frequently associated with the problematic organism Renalcis (the affinities of Renalcis and the equally problematic Epiphyton are discussed in Appendix IV). All coelobiontic organisms require a steady water flow to provide nutrients and oxygen, and to remove any toxic waste products (Kobluk, 1981). Water circulation is also necessary to wash in the fine, peloidal sediment. Burrow cavities are of small diameter, lacking sharp margins but only rarely showing signs of sediment disturbance or diagenetic alteration of areas around the burrow. Similar burrows, described by Kobluk (1980, p.51) were interpreted as representing traces of either the feeding activities or habitation burrows of indeterminate small worms.

The areas of cavities not filled with sediment are occupied by clear, near equant calcite mosaic, Plate 3:17, Fig. 2. No cement fabrics, such as radiaxial-fibrous mosaic (Kendall and Tucker, 1973, Bathurst, 1976, 1977) fasicular-optic calcite (Kendall, 1977), divergent radial mosaic (Mazzullo and Cys, 1979), indicative of a former aragonitic, marine phreatic (Longman, 1980) cement are seen within the cavities. Neither, as far as can be determined, do the cements present show features indicative of a vadose diagenetic environment. The absence of extensive dissolution of the limestone, with associated vug and secondary cavity formation, supports the

Plate 3.17

Figure 1.

Cavity within Auchensoul Limestone Member algal boundstones, showing infilling by peloidal carbonate sills. The cavity, which may be of burrow origin, has an encrustation, perhaps of the problematic alga *Epiphyton*, on its roof.

Thin section, AUR/1/79, plane polarised light.

Figure 2.

Clear, near equant, calcite spar infilling cavity in Auchensoul Limestone Member algal boundstone.

Thin section, AUR/1/79B, plane polarised light.

Figure 3.

Highly fractured laminated calcarceous mudstones interpreted as having infilled a large-scale cavity system within the Auchensoul Limestone Member at Doularg.

Cut surface.

Specimen, DH/1/79.

Plate 3.17

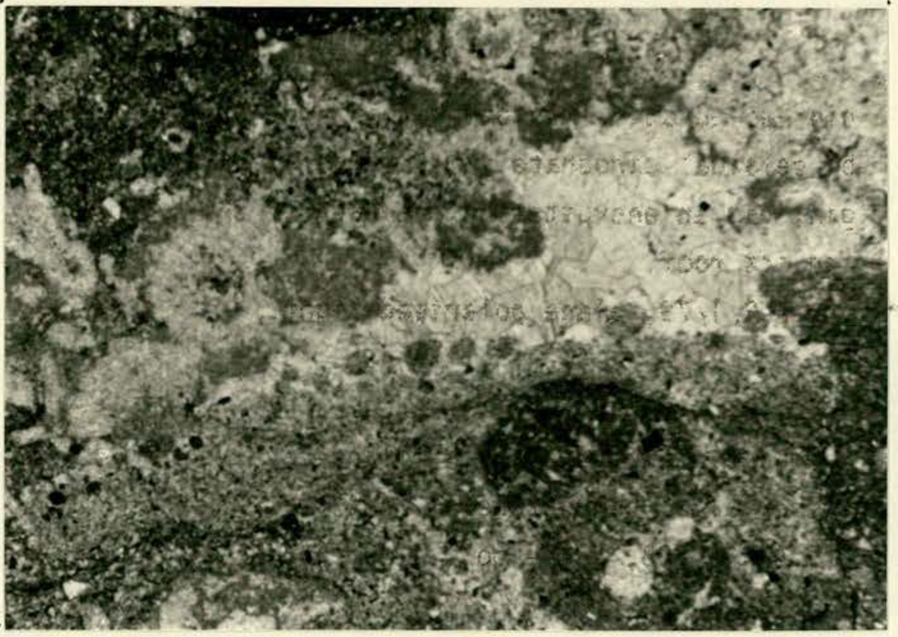


Figure 1

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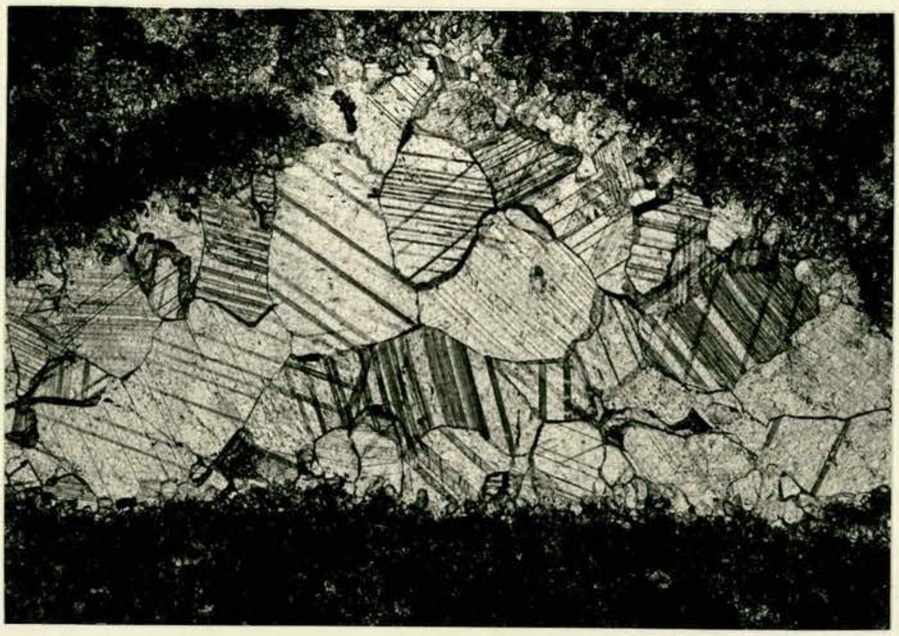

Figure 2

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Figure 3

conclusion that freshwater, vadose diagenesis did not affect the limestone member at the R. Stinchar locality. Cements present are thought to have developed as a result of saturated freshwater phreatic or more probably burial diagenesis. The lack of any distinctive cement fabric precludes a more definite conclusion.

Doularg Hill

Exposures in a disused quarry on Doularg Hill, noted by Williams (1962), are the only outcrops of the member S. of the Stinchar Valley that are currently available. Williams records 60 feet of section but infilling has reduced this to 4-5m. Lithologies present include moderately pure algal boundstones, and, algal chip grainstones, Plate 3:18, calcareous medium and coarse sandstones and laminated, peloidal calcareous siltstones, Plate 3:17, Fig. 3, all of which are strongly reddened. No meaningful sedimentological section can be determined as the section is cut by numerous, closely spaces shear planes, which obscure primary, depositional relationships.

The algal boundstones, Plate 3:18, contain an algal flora identical to that seen at the other localities. Girvanella is again the dominant component, in places forming large, coalescing growths, Plate 3:18, in which the filaments are aligned parallel to an undulose growth surface. Lithistic sponges, often degraded to a pseudo fenestral texture, Plate 3:19, Fig. 1, are also present, frequently being encrusted by coccoid and filamentous (girvanellid) algae, Plate 3:19, Fig. 1). Poorly preserved tubular, sponge-like organisms with a porous internal structure are present in small numbers. These organisms may be up to 3.0-3.5cm in overal diameter, often flattened, with a central inner area 1.5-1.8cm in diameter that lacks the porous, radially fenestral structure of the 0.7cm thick walls. The general structure is closely similar to that described by Alberstadt and Walker (1975) from organisms interpreted as calathids (possible receptaculitids, Dasycladaecean algae,(Nitecki, 1967)) or sponges, Foster (1973), Alberstadt and Walker (1975).

Algal chip grainstones are an important lithology in the Doularg exposures. Platey algal grains in which the Girvanella filaments have a near parallel alignment, are the main component, over 50% of grains present, Plate 3:19, Fig. 2. Pelmatozoan debris is usually surrounded by large, well developed syntaxial overgrowths, Plate 3:19, Fig. 3. The sandstones are composed of similar lithic material to

Plate 3.18

Negative print of thin section, showing both algal chip grainstones, in upper part of plate and _Girvanella_ boundstones in the lower part. A dissolution cavity, infilled by calcite spar occurs in the lower part of the plate.

Thin section, DHX/1/79.

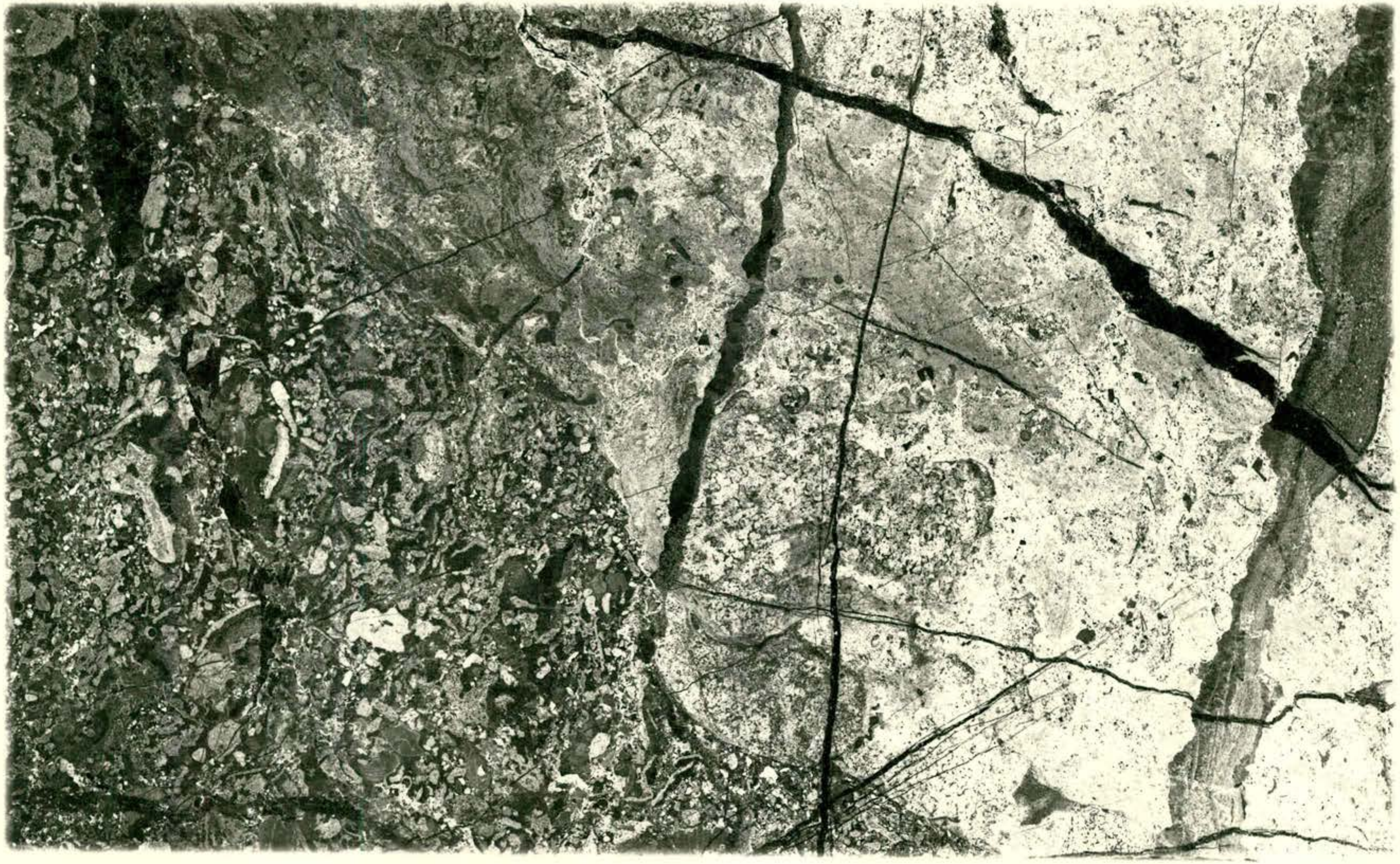

Plate 3.19

Figure 1.
Encrustation at partially degraded lithistid sponge by poorly preserved _Girvanella_ filaments.
THin section, DH/2/79A.

Figure 2.
Platy fragments of disrupted _Girvanella_ mats occurring as detrital grains in algal chip/peloidal grainstone.
Thin section, DHX79A, plane polarised light.

Figure 3.
Crinoidal grainstone cemented by well developed calcite syntaxial overgrowths. In addition to the crinoidal fragments, algal lumps and the problematic alga _Nuia_ are also present.
Thin section, DHX79B, plane polarised light.

Plate 3.19

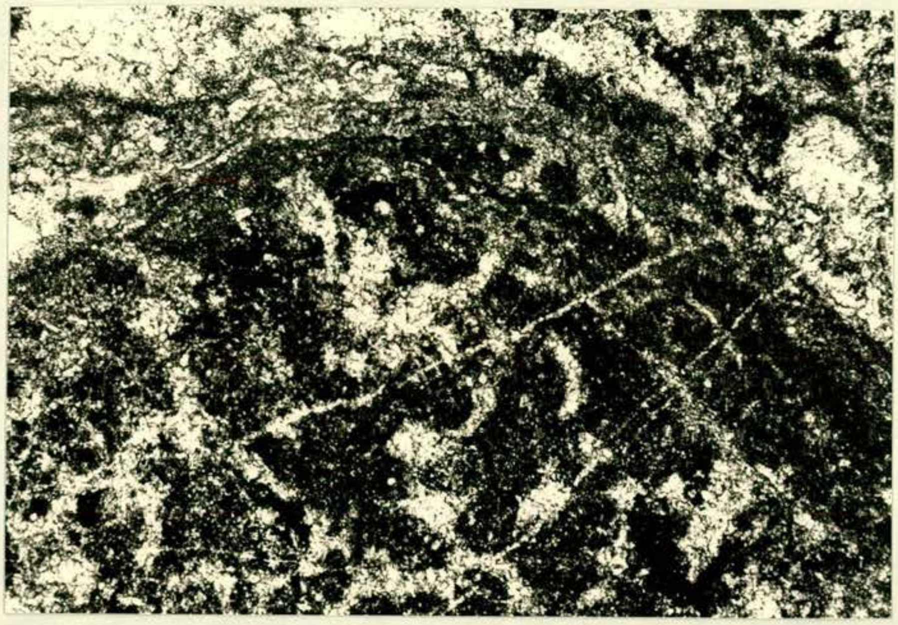

Figure 1

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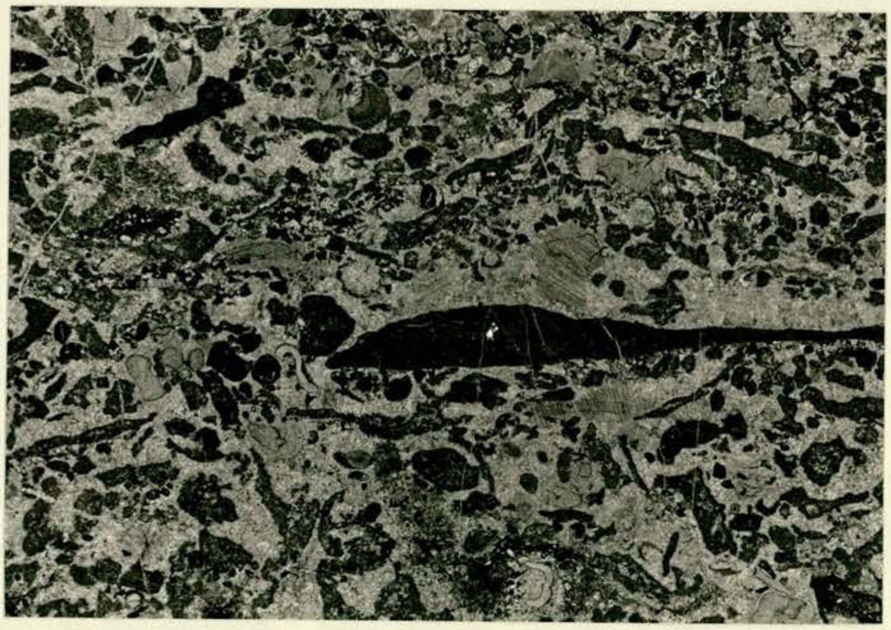

Figure 2

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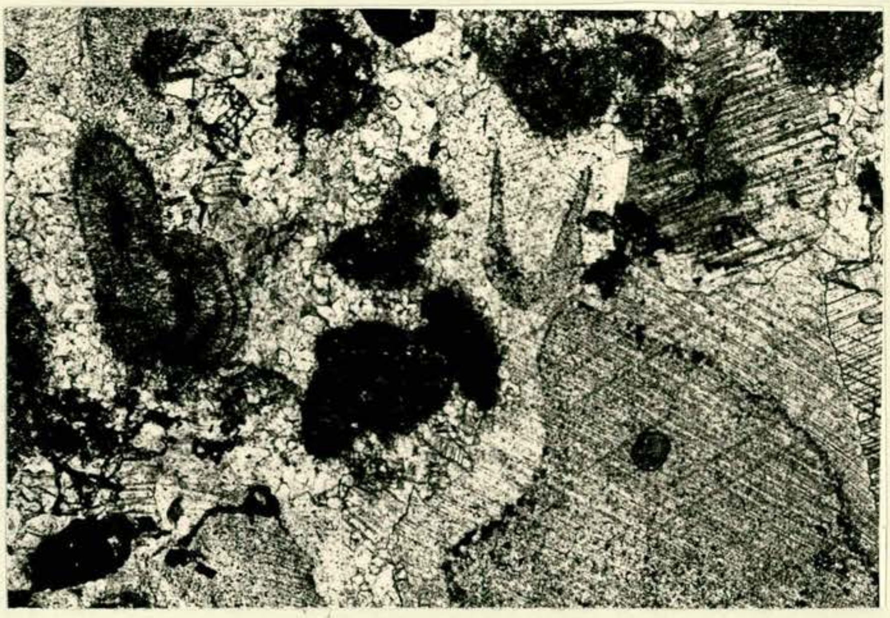


Figure 3

0.5mm

that seen in the Conglomeratic Member matrix being in general well rounded grains of basalt, chert and feldspar. Sorting is good with no matrix present, the sediment being cemented by cloudy calcite.

Laminated, peloidal siltstones occur as either partial or complete fills in large scale, ramifying, secondary, dissolution cavities that cut the other calcareous lithologies, Plate 3:20, Fig. 1. The silts may occur in repeating units, becoming more clearly peloidal and calcareous to the top of each unit, Plate 3:20, Fig. 2, or may be less clearly banded, lacking well developed peloids, but possessing a clotted, grumuleuse fabric, either relict micrite surrounded by neomorphic microspar or altered densely packed peloids (Bathurst, 1976). No coelobiontic encrusting organisms such an inhabit cavities in limestones from the R. Stinchar locality, Craighead Limestone (Chapter 7) or Benan Formation limestone horizons (Chapter 5) are seen in the Doularg cavities. Cavity roofs are sharp and may truncate grains and cement in the grainstones and boundstones, although the relationship is frequently confused by clay seam formation along cavity margins. The laminated silts geopetally infill cavities and in some cases rest on thin cement layers developing on the cavity floor, Plate 3:20, Fig. 3, this alternation being repeated several times in certain instances. Fallen blocks of grainstone or boundstone may occur either in the cavity sediment or in the coarse cloudy non-ferroan spar which infills the parts of cavities not occupied by sediment, where they act as substrates and centres for radial growths of the void filling spar.

The cement itself develops equally from both roof and floor cavities, unless interupted by an influx sediment. The fabrics displayed include one similar to that described by Bathurst (1976) as radiaxial-fibrous, Plate 3:20, Fig. 3, although much of the cement is bladed, non fibrous. Whilst a fibrous texture may still be visible in parts it is not possible to determine whether a divergent radial mosaic, or others, more clearly suggestive of a former aragonitic mineralogy, marine phreatic diagenetic environment (Mazzullo and Cys, 1979, Maxxullo, 1980) is present.

The cavities themselves probably formed in the freshwater, either vadose or phreatic, environment, both undersaturated with respect to $CaCO_3$. In general form the cavities, their internal sediments and cements closely resemble certain of the cavities

Plate 3.20

Figure 1.
Ramifying dissolution cavities, partially infilled by calcareous mudstones, cutting sandy limestone of Auchensoul Limestone Member, Doularg Hill. The upper parts of the cavities are infilled with calcite spar. Cut surface, specimen no. DH/2/79.

Figure 2.
Successive units of calcareous mudstone infilling inferred dissolution cavity. Each unit is separated by a compaction produced clay seam (non-sutured-seam stylolite) whose formation clearly postdates the carbonate veins that cross cut the mudstones.
Thin section, DH/1/80, plane polarised light.

Figure 3.
Complex calcite cements in dissolution cavity. The cements in the upper left show fabrics comparable to the radiaxial-fibrous fabrics described by Bathurst (1976). In the lower right, thin cement horizons are inter-laminated with thin partings of calcareous mudstone.
Thin section, DH/X/79A, plane polarised light.

Plate 3.20

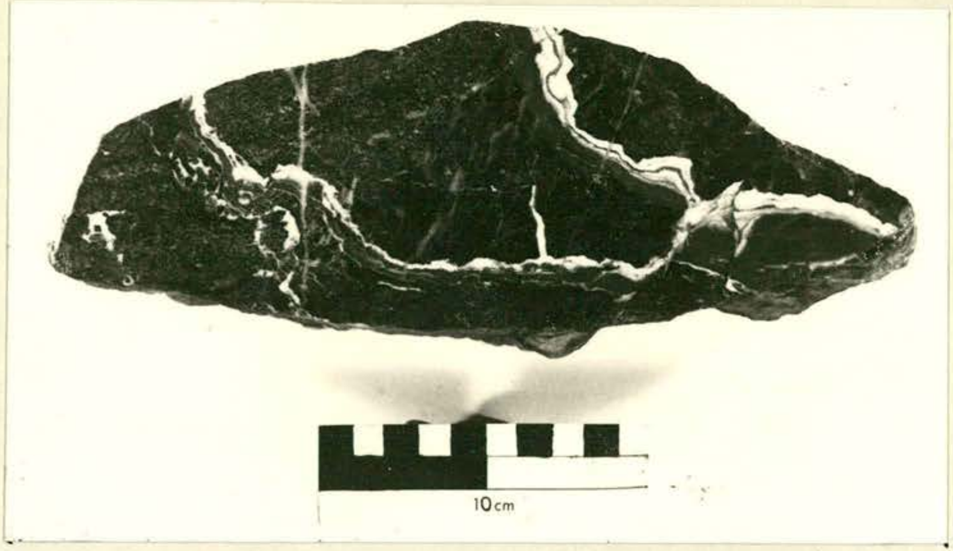


Figure 1

Figure 2

3mm

Figure 3

1.5mm

developed in the Waulsortian lime mudbands of Ireland, described by Lees (1964) and the similar facies development seen in Dinantian rocks of the Clitheroe area, Yorkshire described by Miller and Grayson (1972) and authors own observations. Such fissures have been interpreted by Miller and Grayson as palaeokarstic features developed as a result of emergence and vadose dissolution of the lime mud bank. An active flow of water in the cavity system is indicated by the sediment fills. The presence of isopachous cements developing from both cavity roof and floor indicates complete filling of the cavity space by $CaCO_3$ saturated waters. Pendant and meniscus cements formed as a result of partial cavity filling by fluids in a vadose environment are absent. Bladed, isopachous cements are considered to be indicative of an active freshwater phreatic environment (Longman, 1980).

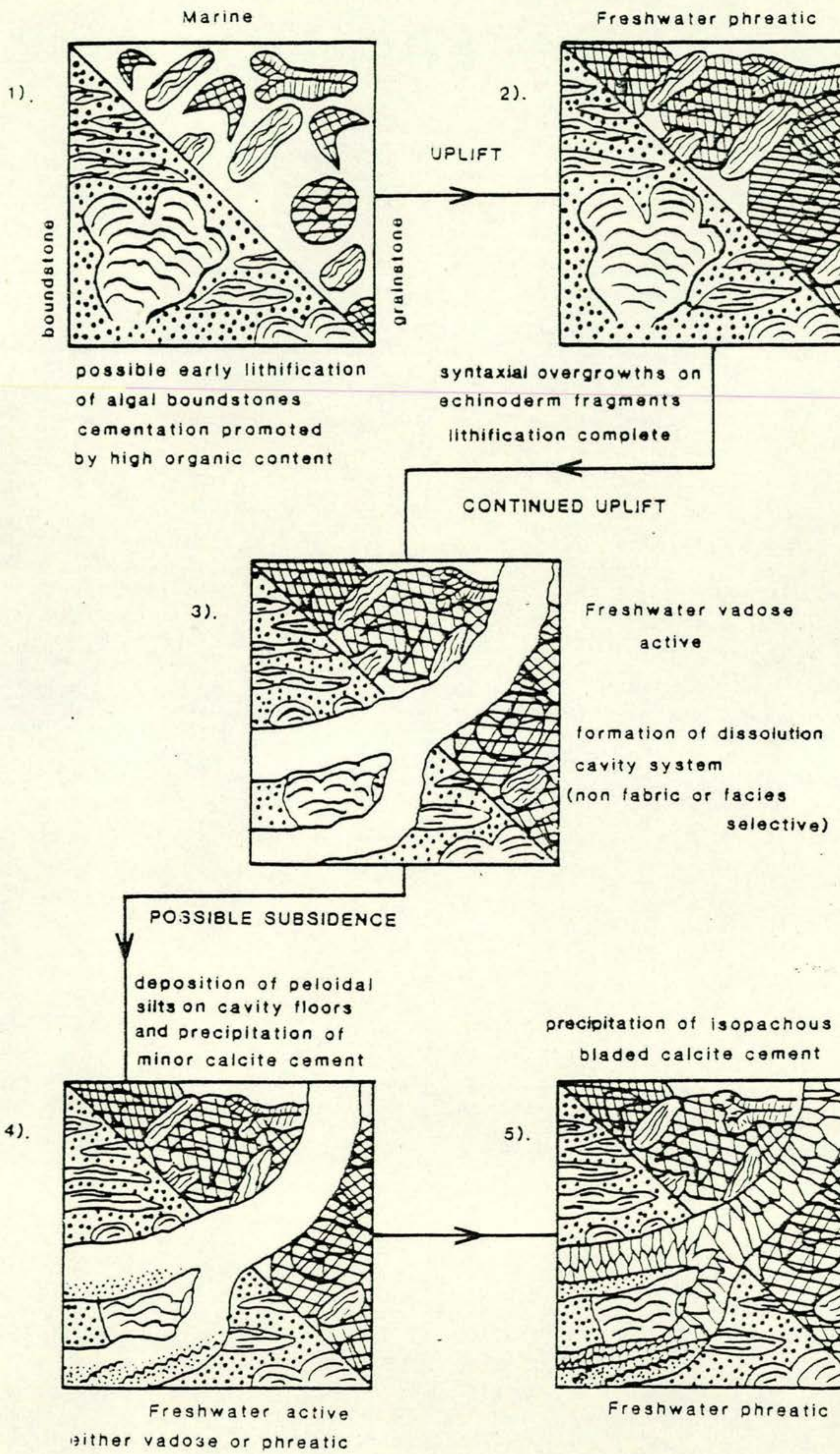
The occurrence of well developed, thick, syntaxial overgrowths on echinoderm fragments in the algal chip grainstones is additional evidence of freshwater phreatic diagenesis. Syntaxial overgrowths that completely surround the host grains, such as those seen in Plate 3:19, Fig. 3, are restricted in occurrence to the aforementioned environment (Longman, 1980). Incomplete overgrowths may occur in the vadose system, in marine environments an isopachous aragonite or high Mg- calcite surrounds the grains (Longman, 1980). The syntaxial overgrowths cannot, however be attributed to the same diagenetic event as the cavity filling cements, as cavities cut both grains and cement in the grainstones. Thus the development of the cavity system must postdate the cementation of the grainstones, and also the boundstones, although there is no evidence available that defines a diagenetic environment for the latter lithology. The proposed diagenetic evolution of the Doularg carbonates is summarised in Fig. 3:13.

In terms of depositional environment a lack of conclusive evidence is again afforded by the Doularg exposures. A number of points are, however, important in determining a possible environmental setting.

(1) The carbonate sequence represents a thicker development within the member of this general lithology than is seen elsewhere.

(2) The algal flora is indicative of shallow marine conditions.

Summary of Auchensoul Limestone Member diagenesis, Doularg Hill.



(3) The occurrence of algal boundstones may suggest a 'reefal' environment.

(4) Subaerial exposure of the Doularg sediments may indicate a tectonic independence from the main areas of Barr Group sedimentation, in which there is no firm evidence for emergence at equivalent stratigraphic levels.

Thus it would seem unlikely that an actual drop in sea level was the cause of emergence of the Doularg carbonates.

(5) The lack of biostratigraphic control on the age of the sequence does not allow accurate time relationships with the type Barr Group sections to be determined. Therefore the somewhat isolated Doularg sequence, deposited in a shallow water setting, assumed to be removed from the main area of Barr Group sedimentation, may, in its thicker development, represent a different, perhaps longer, time interval than other exposures of the member seen elsewhere.

Thus the Doularg sequence may be tentatively interpreted in terms of a reefal environment for the algal boundstones with associated non reefal both calcareous and clastic, higher energy, shallow marine deposits. The source for the clastic detritus may have been local, suggested by the coarse grained nature of the Doularg clastics as compared with the clastic Auchensoul Mudstone Member exposed in the R. Stinchar section that separates Doularg from the main area of shallow water sedimentation. Additionally the Doularg sequence may represent a shallower water environment that is seen in the R. Stinchar exposures, see section 3.5. It is not therefore unreasonable to propose that these shallow water carbonates and clastics accumulated on a palaeohigh of uncertain nature that was tectonically independent of the areas to the N., this suggestion is discussed in a broader context in Chapter 6.

3.5 Auchensoul Bridge Mudstone Member

The above unit comprises a lithologically variable sequence of sandstones, silty mudstones and muddy limestones, Fig. 3:12, exposed only in the bed of the R. Stinchar upstream from the bridge to Auchensoul Farm.

As outlined in section 3.4 the mudstone member occurs both above and below a carbonate horizon thought to represent the local development of the Auchensoul Limestone Member (Williams, 1962). Below the 2m thick limestone horizon the sequence is composed of non-bioturbated, indistinctly bedded, interlaminated medium to fine sands with silty horizons, coarsening downwards towards the top of the Conglomerate Member. The lowest few metres of the unit lack bioclastic material. Detrital grains present are indicative of the same, Ballantrae Complex, source area as other clastic units in the Kirkland Formation. Large, secondary growths of chlorite with parallel aligned cleavages occur in the matrix of the coarser grained horizons, Plate 3:21, Fig. 4, possibly indicating ultradiagenesis or low grade metamorphism and mineral growth. Passing upwards towards the limestone member bioclastic material becomes increasingly more abundant, brachiopod, bivalve and algal, Nuia and more rarely Girvanella, being present, Plate 3:21,Fig. 3. In places the sediment is clearly calcareous, more limey patches being separated from each other by often extensively developed compactional clay seams, giving a nodular appearance, although no actual nodules are developed.

Above the limestone horizon the mudstones are noticeably finer grained, being silty rather than sandy, and more calcareous. Various fossiliferous horizons are present, gastropods and the red alga Solenopora, are most noticeable, with possible calathids also present. Bioturbation is locally extensive, burrow traces belonging to the ichnogenus Chondrites often being abundant and well preserved, indicating slow sedimentation rates and a lack of physical reworking (Byers and Stasko, 1978). Throughout the mudstone member a very dusky red colouration predominates, although non-oxidised, greenish grey horizons do occur.

Bioclastic grainstones, are sporadically developed and represent a higher degree of sediment sorting than is seen elsewhere in the section. Such developments may have formed as a result of winnowing during the passage of abnormal storm events, in a manner similar to bioclastic grainstones occurring in an offshore mudstone sequence described by Spechte Brenner (1979) from the Jurassic of E. Central Wyoming.

In general the most abundant fossil remains are comminuted shell material, with ostracods and Saccaminopsis/Thuraminoides tests being common and frequently preserved intact. Nuia is present throughout the sequence. Such body cavities may be infilled completely with sediment or may be partially infilled by cement, Plate 3:21, Figs. 1 & 2. Fig. 2 shows the development of finely fibrous, isopachous cement rims on both internal and external surfaces of the shell, the fibres have a radial divergent, botryoidal habit, suggesting a former aragonitic mineralogy (Mazzullo and Cys, 1979, Mazzullo, 1980). Plate 3:21, Fig. 1 shows a thick radiaxial fibrous cement with less well developed, more fibrous, calcite, occurring only on the internal surface of the shell. Both body cavities are also partly infilled with sediment of the same type as that surrounding the shells, the infilling of the shells occurring after the development of the cements. The cements shown in the two examples and elsewhere throught the Mudstone Member are thought to represent a former aragonite or Mg calcite marine cement, similar to those described from Recent carbonates by James et al. (1976), Ginsburg and James (1976) and from ancient deposits by Mazzullo and Cys (1979). Skeletal material may be micritised as shown by the ostracod and trilobite debris in Plate 3:21, Fig. 1, the process having occurred prior to cement development, probably as a result of the activity of algae, fungi and bacteria in the stagnant marine phreatic environment (Longman, 1980).

The Mudstone Member with its associated development of the limestone member is interpreted as representing a shallow marine environment, possibly somewhat offshore from the sequence seen along the N. side of the Stinchar Valley. Deposition took place below both normal and storm wave base, although probably affected by rare, extreme storm events. A major break in fine clastic sedimentation resulted in clearer water conditions, allowing colonisation by the various algae seen in the limestone member. Input of clastic material decreases throughout, although the concomitant increase in carbonate content only rarely resulted in the formation of true limestone horizons.

Plate 3.21

Figure 1.

Thick radially arranged fibrous calcite cements partially infilling interior of articulated ostracod test. The sediment is composed dominantly of silty mud, but bioclastic grains, e.g. micritised trilobite fragment, are also present.

Thin section, AUR/13/80, plane polarised light.

Figure 2.

Botryoidal, fibrous, calcite cements in ostracod body cavity. Both cement and test wall are neomorphosed.

Thin section, AUR/4/80, plane polarised light.

Figure 3.

Moderately abundant bioclastic material brachiopods (B) and the problematic alga Nuia (N) in calcareous mudstone.

Thin section, AUR/6/80, plane polarised light.

Figure 4.

Large, well formed chlorite crystals (C) with parallel aligned cleave-ages in coarser grained fine to medium sand horizon of Auchensoul Mudstone Member.

Thin section, AUR/5/80, plane polarised light.

Plate 3.21

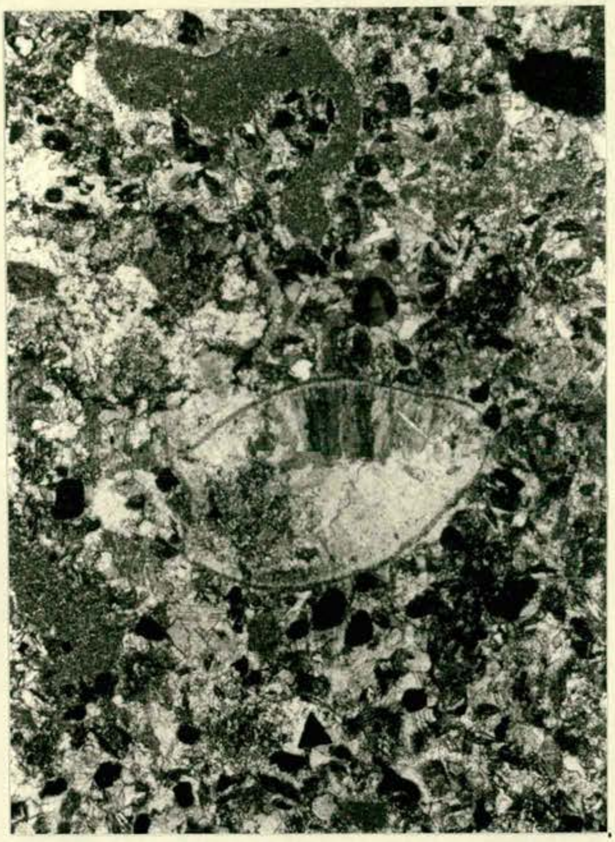


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Figure 1

0.7mm

Figure 2

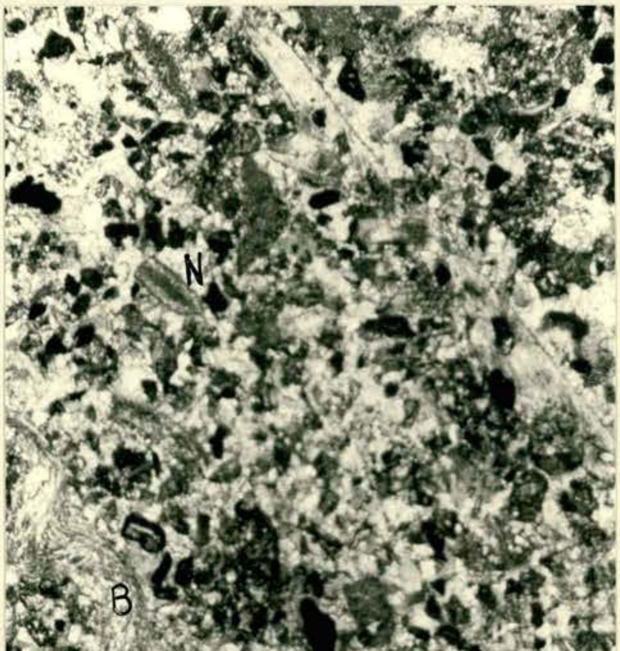

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Figure 3

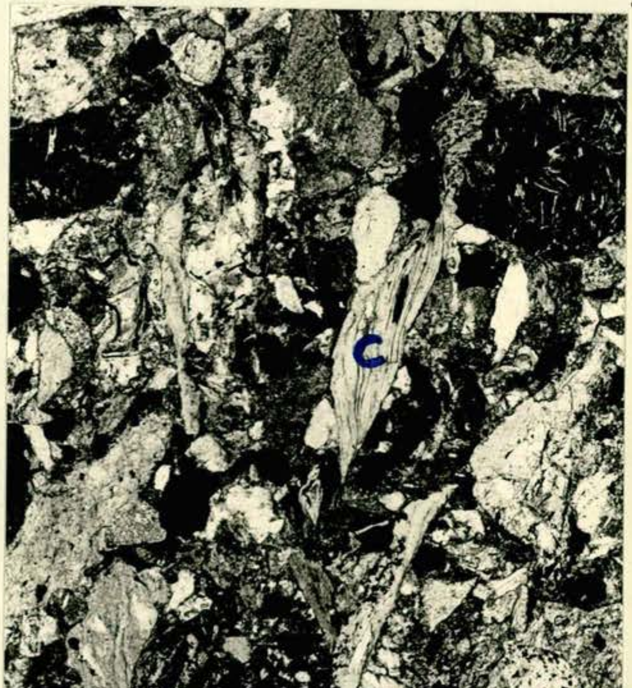

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Figure 4

3.6 Summary

The depositional history of the formation, summarized in 'cartoon' form in Fig. 3:14, is thought to be as follows: The Conglomerate Member of the Formation is inferred to rest unconformally upon the Ballantrae Igneous Complex, although the junction is not exposed, and is the oldest unit in the Girvan sedimentary sequence. The primary sedimentary features of the Conglomerate Member, imbrication style, clast shape, fabric and bedding are thought to indicate deposition on a coastal alluvial fan or in the immediately adjacent submarine areas. A decrease in sediment supply to the inferred fan is indicated by a crude fining towards the top of the Member.

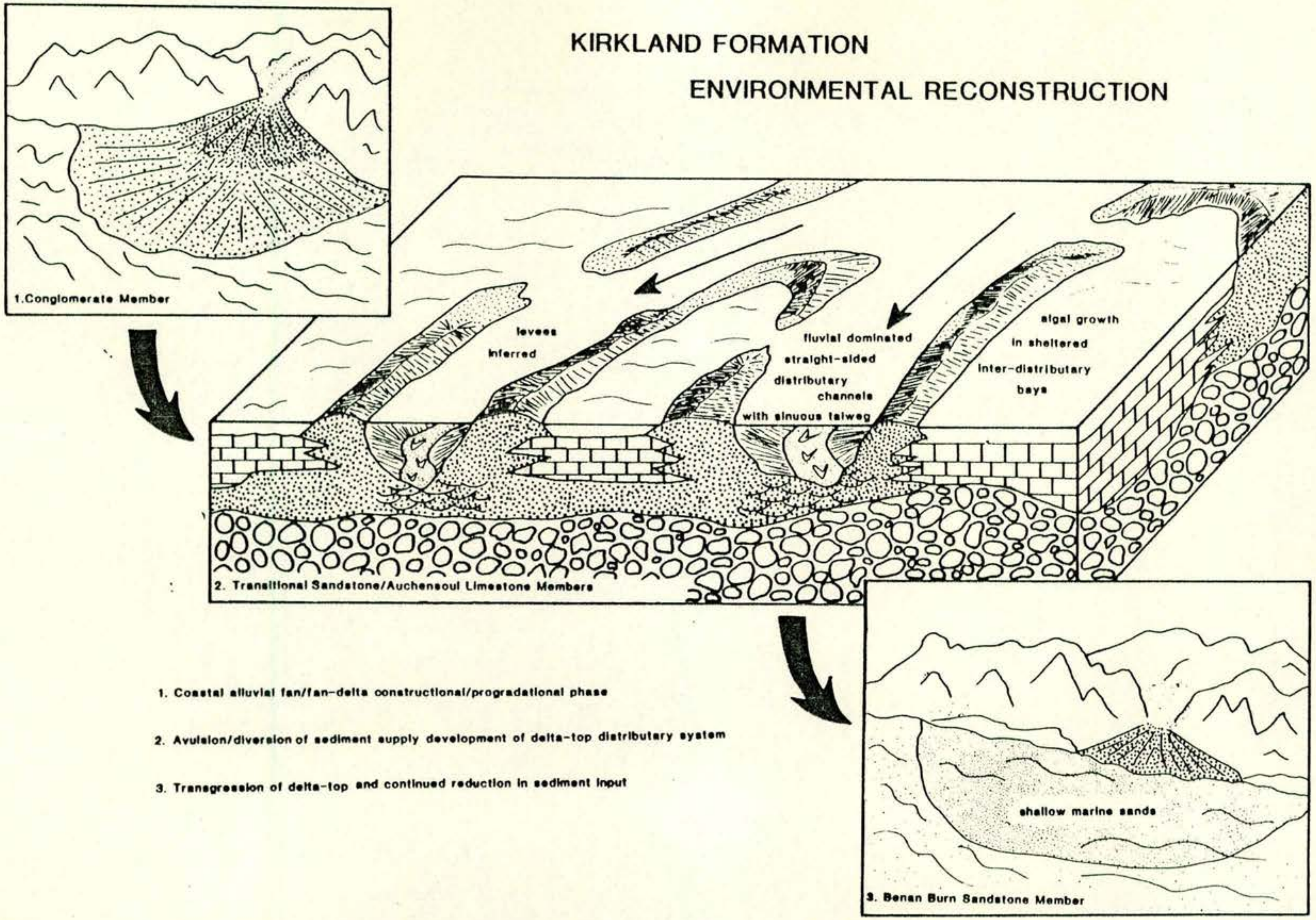
The overlying Transitional Sandstone Member is markedly more fine grained, indicating continued fan abandonment, and is interpreted as representing a fan-delta top distribution channel system. The laterally equivalent Auchensoul Limestone Member is composed largely of the remains of calcareous algae, and contains an impoverished marine fauna. The unit is thought to have accumulated in an interdistributary bay, although a coastal lagoon environment cannot be discounted.

The fully marine nature of the overlying Benan Burn Sandstone Member indicates transgression of the former fan-delta top. Continued decrease in sediment grain size throughout the Member, culminating in the establishment of carbonate, Stinchar Limestone Formation, sedimentation, documents the final abandonment of this particular fan-delta.

Away from the main area of Kirkland Formation deposition, reddened limestones outcropping on Doularg Hill and correlated with the Auchensoul Limestone Member are interpreted as part of a shallow water algal 'reef' or 'mound'. The diagenetic fabrics of this limestone indicate a period of cavity formation, possibly in a freshwater vadose environment. It is thought that this unit evolved separately from the main part of the Formation, on and around an offshore palaeohigh, and might in fact be best placed within the Traboyack Mudstones, see Chapter 6.

The Kirkland Formation sequences, interpreted as fan-delta deposits indicates transgression of the Ballantrae Igneous Complex basement during the Llanvirn or possibly the uppermost Arenig.

Figure 3.14


KIRKLAND FORMATION
ENVIRONMENTAL RECONSTRUCTION
1.Conglomerate Member
levees
inferred
fluvial dominated
straight-sided
distributary
channels
with sinuous talweg
algal growth
in sheltered
inter-distributary
bays
2. Transitional Sandstone/Auchensoul Limestone Members
shallow marine sands
3. Benan Burn Sandstone Member
1. Coastal alluvial fan/fan-delta constructional/progradational phase
2. Avulsion/diversion of sediment supply development of delta-top distributary system
3. Transgression of delta-top and continued reduction in sediment input

This rise in sea level followed a eustatic drop in sea levels during the Middle Arenig. Transgression of the Ballantrae rocks cannot, however, account for the distribution and thickness of the Kirkland Formation. It is felt that subsidence along a major, S.W.-N.E. trending fault, in the Assel Valley allowed the accumulation of the fan-delta deposits and restricted their occurrence to areas S. of this fault. This conclusion is in agreement with Williams' palaeogeographic model, but does not necessitate either upward movements along the major faults controlling sedimentation, or dramatic, and frequent, changes in sea level. Instead, a pattern of subsidence only, gradually declining in rate, is envisaged for the Kirkland Formation.

CHAPTER 4

STINCHAR LIMESTONE FORMATION

4.1 Introduction

The varied suite of clastic and carbonate sediments that together constitute the Kirkland Formation fine upwards through the unit and, with decreased clastic input carbonate deposition becomes dominant, marking the passage to the Stinchar Limestone Formation. Three members are recognised within the formation, as outlined in Chapter 2, each representing a distinctive environment or set of environments. In addition, various localities, for which no definite environmental interpretation can be made, or are too poorly exposed and geographically isolated, are broadly assigned to the Formation but not to any specific member. This stratigraphic treatment differs from previous schemes as shown in Chapter 2, and is thought more clearly to reflect the variety of carbonate depositional environments present, as interpreted herein. The following chapter will therefore be organised within this scheme, although a more facies-orientated approach is taken when necessary, to provide a full understanding of the unit.

Previous work

Williams (1962) states that "the Auchensoul Limestone, 'confinis' flags, Stinchar Limestone and 'superstes' mudstones" are "all undoubtedly shallow water deposits". These quotations summarize the extent of knowledge prior to the present work. The general lack of published data on the Stinchar Limestone Formation led Anderton et al. (1979) to question the shallow water nature of the unit, suggesting a deeper water depositional environment. As already stated, in Chapter 3, this question of water depth is critical to a proper understanding of the Barr Group sediments.

4.2.1 Stinchar Valley Member

The localities assigned to this unit, detailed in Chapter 3, outcrop solely along the northern flank of the Stinchar Valley in various disused quarries and stream sections. The thickness of the unit is variable, and the maximum observed development is approximately 65m as seen in Benan Burn and the I.G.S. Benan Burn Borehole, Appendix II. The extent to which the unit is attenuated laterally along the valley cannot be accurately gauged as faulting and erosion have seriously affected the Auchensoul and Minuntion exposures. These differ in that the limestones are more thinly bedded and argillaceous than elsewhere along the Stinchar Valley. Apart from these two exceptions the member is remarkably uniform in facies, both laterally and through time.

4.2.2 I.G.S. Benan Burn Borehole

A cored section through the Member, showing both upper and lower contacts, was obtained during July 1980. As far as could be determined, the sequence, whilst cut by various small faults and veins, was a true reflection of both thickness and stratigraphy. Photographs and detailed descriptions of representative core intervals are present in Appendix II. Fig. 4:1 shows a graphic log of the core section.

Major features of core section through the Stinchar Valley Member of the Stinchar Limestone Formation

(1) The base of the unit is gradational into the underlying Benan Burn Sandstone Member of the Kirkland Formation.

(2) The top of the unit is marked by extremely rapid transition into the overlying Mudstone Member of the Benan Formation.

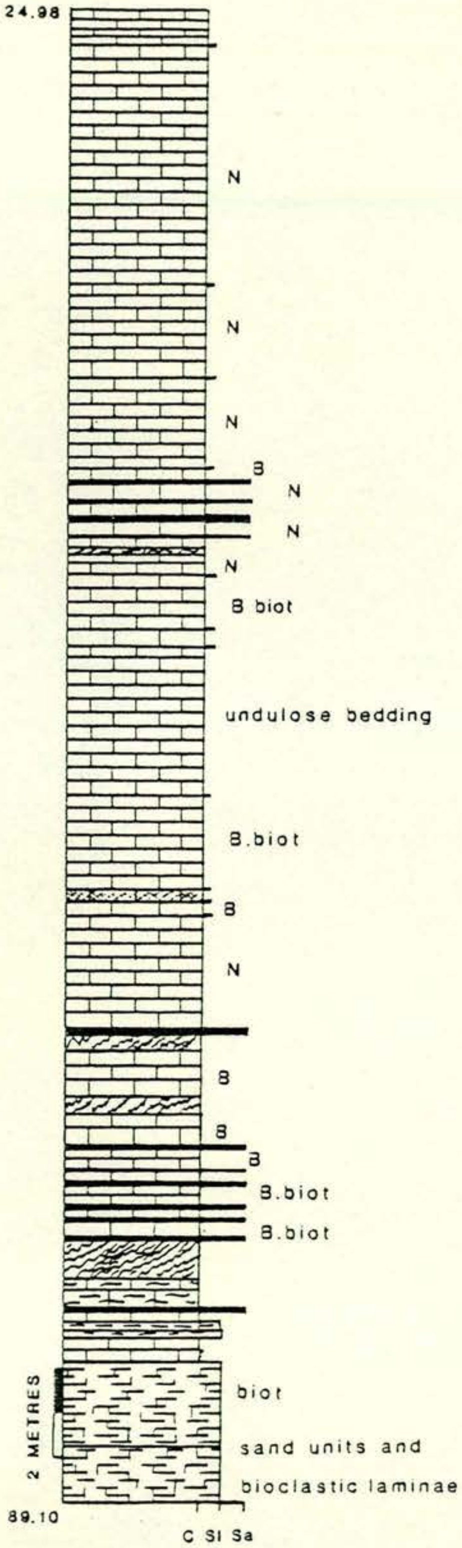
(3) The base of the Member is silty, but the limestones become increasingly pure towards the top of the unit.

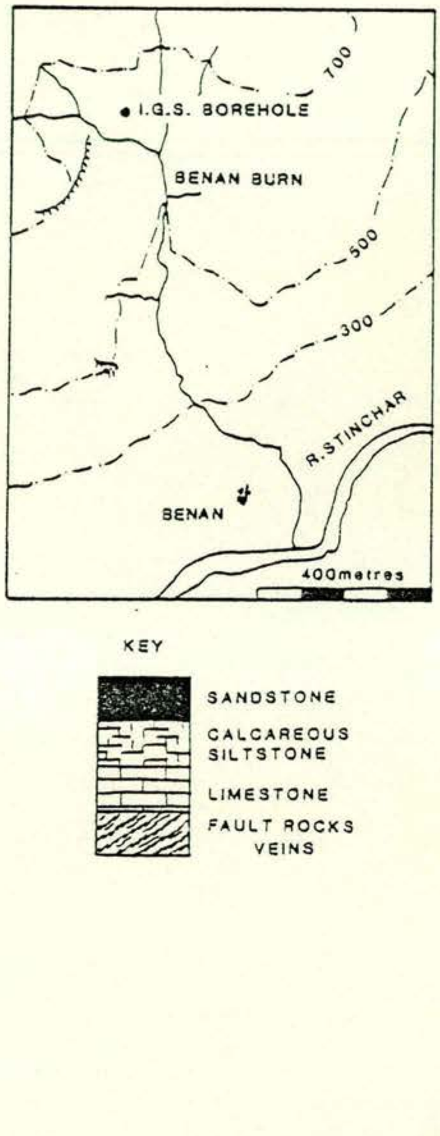
(4) Thin, 3-20cm thick sandstone horizons occur at two broad levels within the Member.

(5) Bioturbation of the limestones is variable in intensity, and is apparently related to the degree of nodularity (non-nodular horizons being noticeably more bioturbated) and therefore also to the point in time at which lithification occurred, see Section 4.2.13.

Figure 4.1

STINCHAR LIMESTONE FORMATION
(STINCHAR VALLEY MEMBER)
BENAN BURN BOREHOLE





(6) Possible hardgrounds occur at various levels in the upper part of the cored section. These horizons are comparable to those seen at a similar stratigraphic level in the small disused quarry (NX29 2385 9275) between the two branches of Benan Burn.

(7) Oncolites and other algal growths occur throughout the Member. Filamentous blue-green algae, Girvanella, dasycladacean green algae, Mastopora and Intramurella and the problematic codiacean green alga, Nuia, are all present.

4.2.3 Microfacies and Petrography

Four carbonate microfacies, A. B. C. D, recognised on the basis of petrography and bedding characteristics, are present in the Stinchar Valley Member, each thought to reflect a subtly different set of depositional conditions. In addition to the carbonate microfacies one non-carbonate lithofacies is present, which although not volumetrically important provides information of critical environmental value. The following sections are given over to description and interpretation of these different components of the Member, first, however, the petrographic features that are common to all microfacies are described.

4.2.4 Petrography

In terms of the classification proposed by Dunham (1962) the limestones of the Stinchar Valley Member are wackestones and packstones, with minor intraclastic conglomerates (microfacies D). There is no significant variation in composition of the wackestones and packstones that constitute the various microfacies,skeletal grains present are as listed below.

(a) Sponge spicules: these are dominantly calcareous monaxons and tetraxons, Plate 4:1, Fig. 1; rare siliceous spicules are also present, Plate 4:1, Fig. 2. Sponge debris is an important fine grained component of all microfacies.

(b) Algae: a variety of taxa, growth forms and grain types are present within the member; a full description of the flora is given in section 4.2.20. Algae and algal grains are important throughout the unit.

Plate 4.1

Figure 1.
Cluster of calcareous monaxon sponge spicules (arrowed) contained within a matrix of dense, 'clotted', algal wackestone. In addition to spicules, ostracod and foraminiferid material is also present. The section is cut by a non-sutured seam stylolite, with clay minerals concentrated along it.
Thin section, 29.25m, plane polarised light, Benan Burn Borehole.

Figure 2.
Single siliceous sponge spicule (arrowed) in 'clotted' algal wackestone. In addition to the siliceous spicule numerous calcareous spicules are also present, constituting a significant grain type and perhaps also a source of fine grained carbonate sediment.
Thin section, 29.25m, Benan Burn Borehole, plane polarised light.

Figure 3.
Articulated ostracod most probably Cythere sp. in faintly peloidal wackestone. The outer surface of the test has a dense micrite coating possibly of algal origin. The test itself is neomorphosed and no original structure is now visible. The body cavity is infilled by an earlier 'dusty' inclusion rich and a later clearer, non-ferroan, calcite cement.
thin section, 71.76m, Benan Burn Borehole, plane polarised light.

Plate 4.1

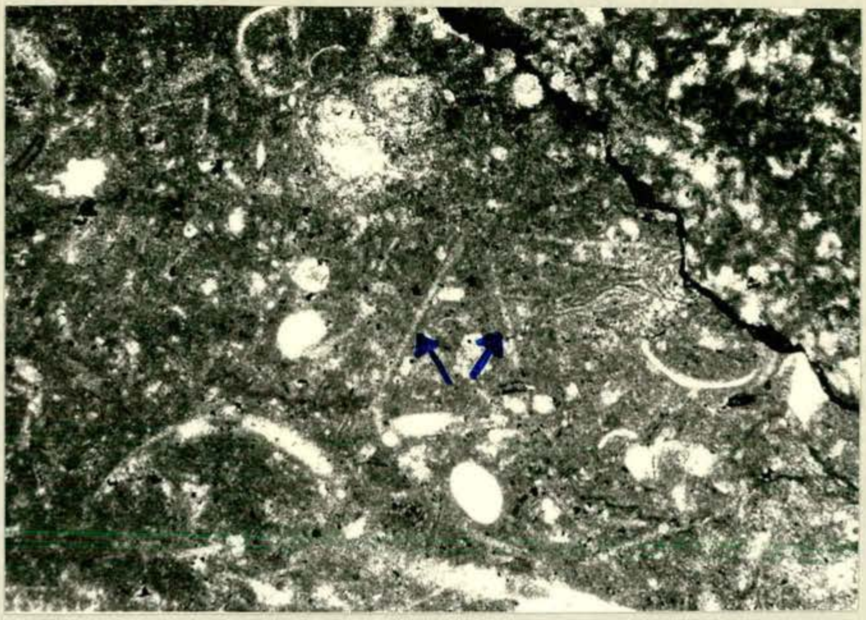


Figure 1

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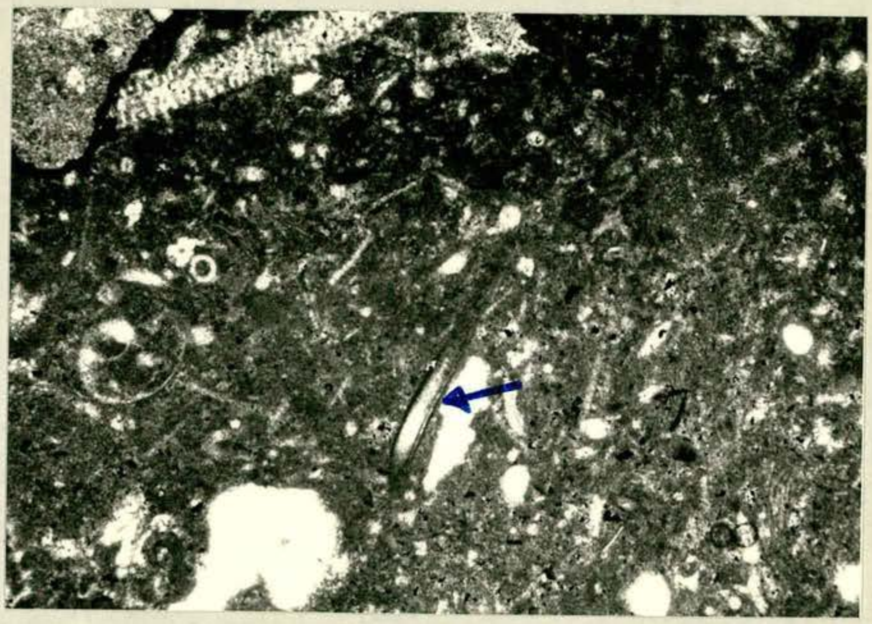

Figure 2

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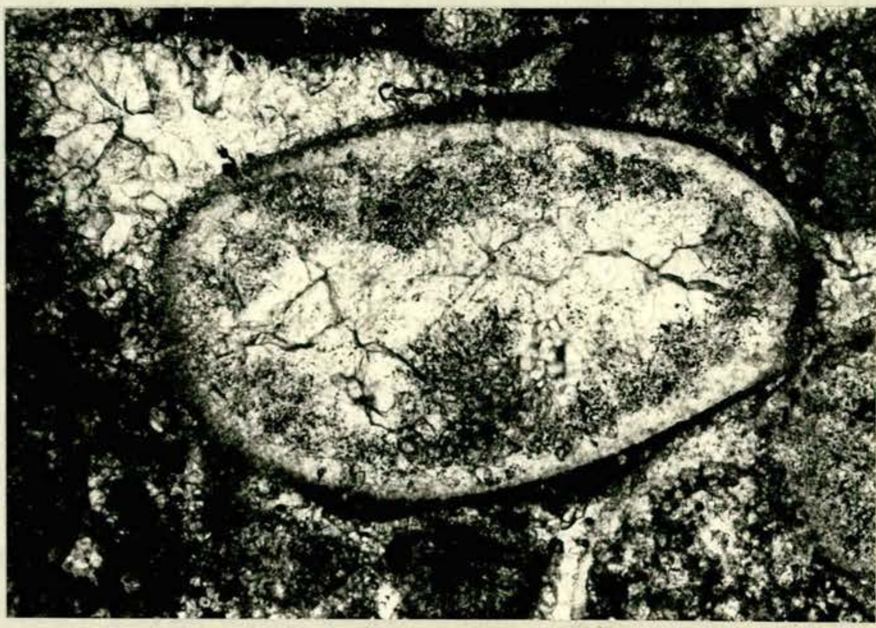

Figure 3

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(c) Ostracods (Plate 4:1, Fig. 3): may be locally moderately abundant. The valves are frequently articulated, and in such cases the body chamber provides one of the few forms of primary, intraparticle, porosity present. Although only usually seen in thin section, only smooth shelled forms are thought to be present. These most probably belonging to the genus Cythere Muller 1785, the only ostracod recorded from the Stinchar Limestone Formation by Nicholson and Etheridge (1888).

(d) Foraminiferids: two forms are present, often in considerable abundance.

(i) Saccaminopsis carteri, Plate 4:2, Fig. 1, a uniserial, thin-walled form with a free test and characteristic vase or sac-like shape when seen in longitudinal section.

(ii) Thuraminoides sp.?, Plate 4:2, Fig. 2. In addition to the sac-like Saccaminopsis a more nearly spherical form with a thicker wall is also present. The interior of the test is often infilled, either partly or wholly, with pyrite, Plate 4:2, Fig. 3. When examined using an S.E.M. a small depression is seen in the surface, Plate 4:3, Fig. 1. Winder (1976) interprets similar objects from Caradocian Trenton Group Limestones of Ontario as having affinities with the foraminiferid Thuraminoides, Plummer, 1945. There is, however, no evidence of the agglutinated wall, characteristic of the genus (Loeblich and Tappan, 1964). The latter authors also indicate that the genus is in fact limited to the Pennsylvanian, in the light of which it may be that the objects described may be a different form of the non-agglutinated Saccaminopsis. The possibility also exists that at least the smaller of these spherical objects, Plate 4:2, Fig. 2 may in fact be calcispheres, thought to represent the reproductive cysts of dasycladacean green algae (Rezak et al., 1971).

(e) Echinoderms: small ossicles, plates and arm fragments are moderately abundant throughout the Member occurring in all micro-facies, and at certain horizons are the dominant grain type present.

Plate 4.2

Figure 1.

The simple foraminiferid Saccaminopsis carteri, showing the characteristic sac-like or vase shape. Both the test wall and the infilling clear calcite spar are neomorphosed.

Thin section, 71.28m, Benan Burn Borehole, plane polarised light.

Figure 2.

Thuraminoides sp?, no wall structure is preserved, having been neomorphosed along with the infilling clear calcite spar. The small spherical object to the left of the larger foraminiferid may be a calcisphere, the fruiting body of a calcareous green alga.

Thin section, 71.28m, plane polarised light.

Figure 3.

Internal cast of Thuraminoides sp? preserved by densley packed aggregates of framboidal and rhombohedral pyrite. Scanning electron micrography.

Insoluble residue, 30m above base of Stinchar Valley Member, Benan Burn.

Plate 4.2

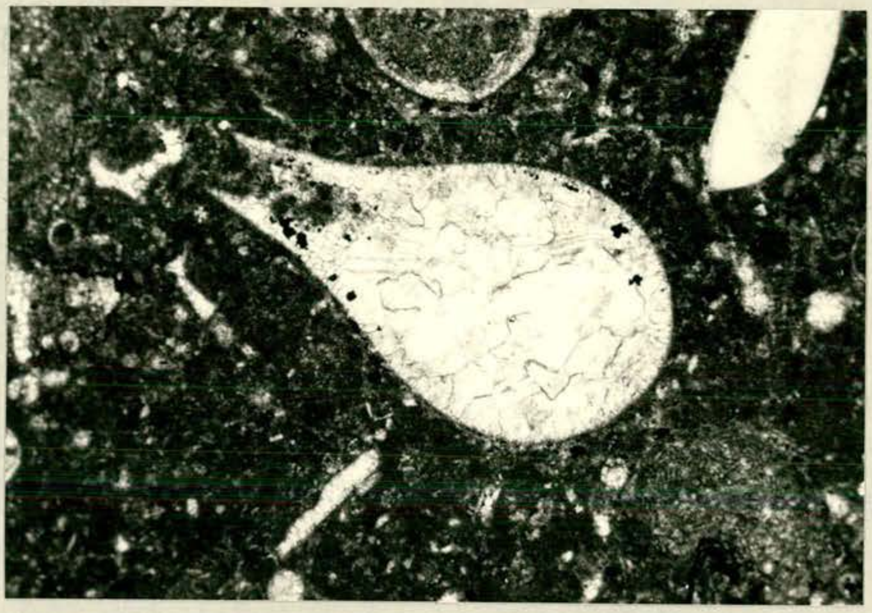

Figure 1

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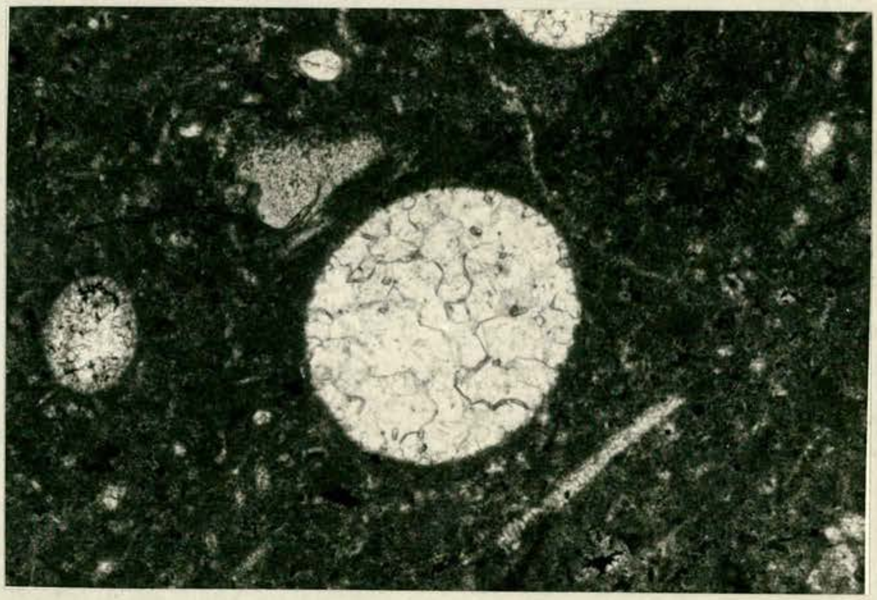

Figure 2

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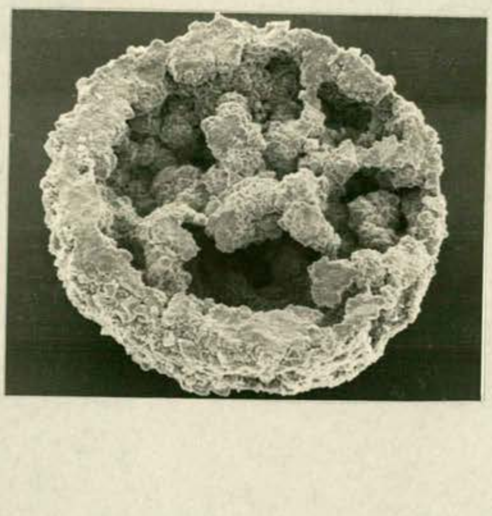

Figure 3

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Plate 4.3

Figure 1.

Thuraminoides sp? preserved by framboidal pyrite cements within the body cavity. The circular depression on the left hand side of the test is tpyical of the genus.

Scanning electron micrograph.

Insoluble residue 20m above base of Stinchar Valley Member, Benan Burn.

Figure 2.

Articulated brachiopod, showing moderately good preservation of original shell structure.

Thin section, 29.25m, Benan Burn Borehole, plane polarised light.

Figure 3.

Abundant trilobite remains, dominantly Illaenus sp. within hardground horizon. Cephalic, pygidial and thoracic fragments are all present. The large dissolution void (arrowed) is infilled by an earlier radiaxial-fibrous, calcite, and later, quartz, void filling cement (a).

Thin section, CB/6/79A, plane polarised light.

Plate 4.3

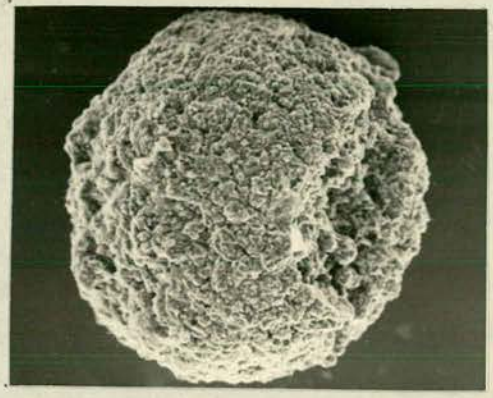

Figure 1

0.75mm

Figure 2

1.25mm

Figure 3

4mm

(f) Brachiopods: are rare, the valves are frequently articulated and closed, Plate 4:3, Fig. 2. Only small, relatively thin-shelled forms are seen.

(g) Trilobites: are in general rare, but may be locally abundant, Plate 4:3, Fig. 3. Complete cross sections, intaglios, and unfragmented exuviae are not uncommon as seen in thin section suggesting relatively little bottom turbulence.

(h) Gastropods: a wide variety of forms is seen in thin section and insoluble residues, the body chambers having in the latter case been infilled with pyrite, ranging from the large Maclurites to small, turritelliform types.

4.2.5 Pre-burial grain modifications

Algal encrustation of skeletal substrates is common, the role of encruster is usually taken either by Girvanella or non-filamentous algae of uncertain affinity. Encrustations may be thick, oncolitic, or thin, consisting perhaps of only a few algal filaments.

Surface borings, Plate 4:4, Fig. 1, and micrite envelopes around grain margins are uncommon in the Stinchar Limestone Formation as a whole but are present throughout. Distinct borings may have been produced either by non-calcareous cyanophyte or chlorophyte algae or by fungi, the agents responsible for microborings in present day carbonate substrates (Friedman et al., 1971) although it is not possible to differentiate between these using the criteria of size and morphology proposed by Bromley (1965). The voids produced by boring organisms may be infilled in one of two ways. Precipitation of a micritic carbonate cement in the voids formed by microboring organisms may eventually result in the formation of a micrite envelope in the manner suggested by Bathurst (1966) although micritisation of the carbonate substrate adjacent to the boring may also result from the metabolic activity of the boring organism (Kendall and Skipwith, 1969). Infilling of the borings with framboidal pyrite may also occur, Bacterial decomposition of organic matter, with the boring, perhaps in this case algal mucilage, results in sulphate reduction and associated sulphide precipitation (see section 4.2.18 for further detail of

Plate 4.4

Figure 1.
Fine borings, infilled with pyrite, of either algal or fungal origin, in neomorphosed gastropod shell.
Thin section, 29.25m, Benan Burn Borehole, plane polarised light.

Figure 2.
Micrite envelopes developed around grains in packstone/grainstone horizon in lower part of Stinchar Valley Member.
Thin section, 71.70m, Benan Burn Borehole, plane polarised light.

Plate 4.4

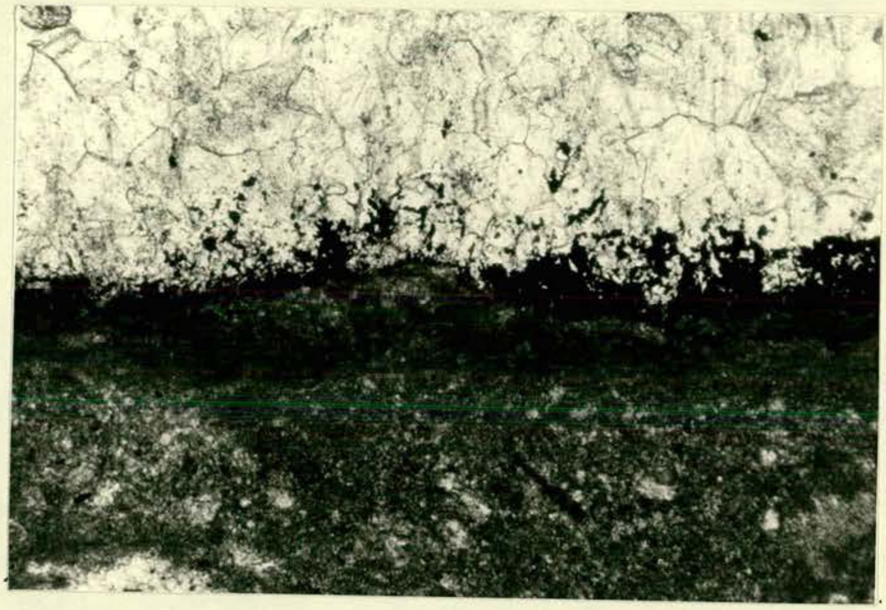

Figure 1

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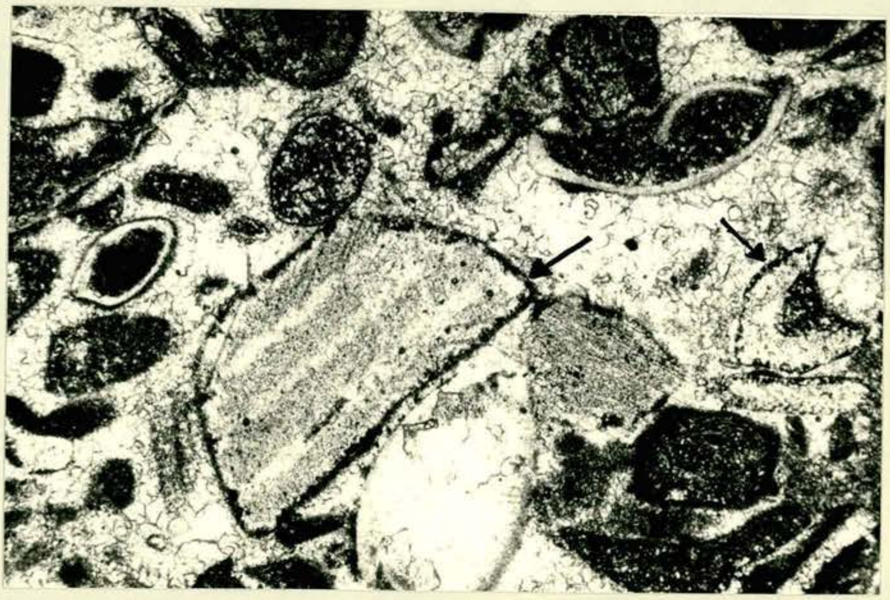

Figure 2

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this process and references). Pyrite framboids and spheres similar to those occurring in the Stinchar Limestone Formation as a whole have been described by Kobluk and Risk (1977) and are similarly interpreted as the result of diagenesis of organic matter.

4.2.6 Microfacies A and B

Microfacies A

Nodular, moderately bioturbated algal/foraminiferal wackestones and packstones. These may occur either as single 'bedded' horizons or may occupy several metres of thickness. There is a clear separation of carbonate and non-carbonate fractions into limestone nodules and inter-nodule silty mudstones. The facies includes all such nodular horizons, regardless of the actual causes of nodularity, there being at least two in the Stinchar Valley Member, see section 4.2.13.

Microfacies B

Non-nodular, heavily bioturbated silty wackestones and packstones. Poorly developed silty mudstone interbeds containing deformed Chondrites burrows which in the more calcareous areas are undeformed, Plate 4:5, Fig. 1. Bedding may be planar or undulose.

As can be seen from Appendix II these two microfacies constitute the two most common bedding types developed in the Stinchar Valley Formation. Together with microfacies C they are thought to form a continuum of bedding types developed in response to varying rates of sedimentation as outlined in section 4.2.14.

4.2.7 Microfacies C - Hardground horizons

Introduction

The planar bedded, encrusted and generally very pure, limestone horizons assigned to this microfacies are frequently developed within the upper part of the Stinchar Valley Member. The best exposed examples are seen in the small quarry between the two forks of Benan Burn (NX29 2385 9275), but are also seen throughout the upper part of the Member where exposed along the Stinchar Valley. In the field microfacies C horizons are most easily recognised by the presence either of large, recrystallized laminar encrusting organisms, probably corals or stromatoporoids, Plate 4:5, Figs. 2 & 3 or equally large upward domed cavities infilled with coarse sparry calcite,

Plate 4.5

Figure 1.
Bioturbated, near planar bedded, oncolitic wackestones, Stinchar Valley Member. The burrows are chondritiform and are dominantly horizontal. Those in the argillaceous interbeds are heavily compacted whereas those in the calcareous beds are relatively uncompacted.

Figure 2.
Hardground horizon from upper part of Stinchar Valley Member. The encrusting organism (a) has grown over the updomed spar filled cavity (b). Cut surface, loose block from Benan Burn quarry.

Figure 3.
Detail of the above figure, showing the development of a pseudo-anticlinal teepee structure and associated breccia. The hardground surface is clearly encrusted by either a coral or stromatoporoid. Within the hardground cavities formed by buckling of the cementing layer are infilled by coarse radiaxial-fibrous calcite cement.
See Figure 2 for scale.

Plate 4.5

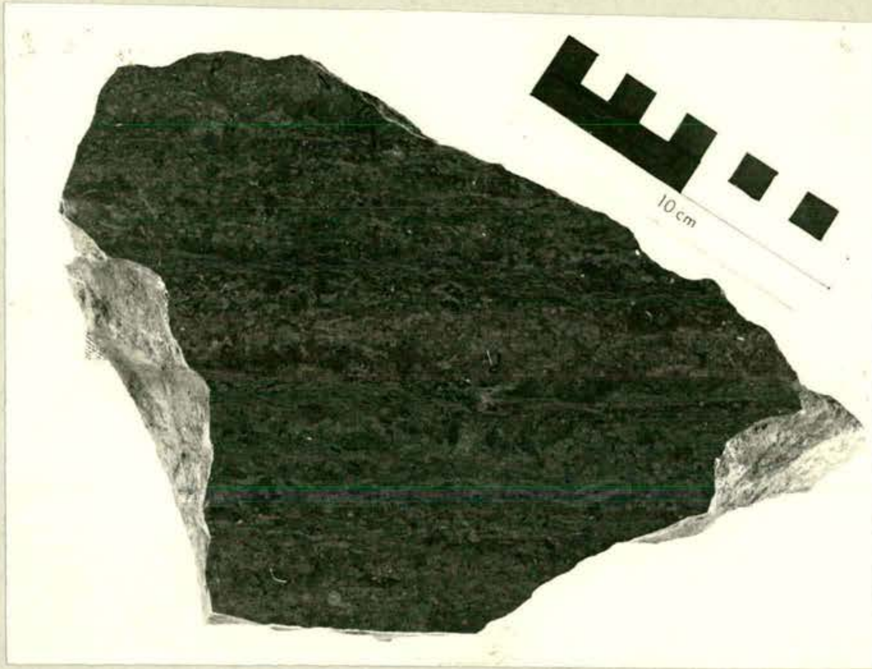


Figure 1

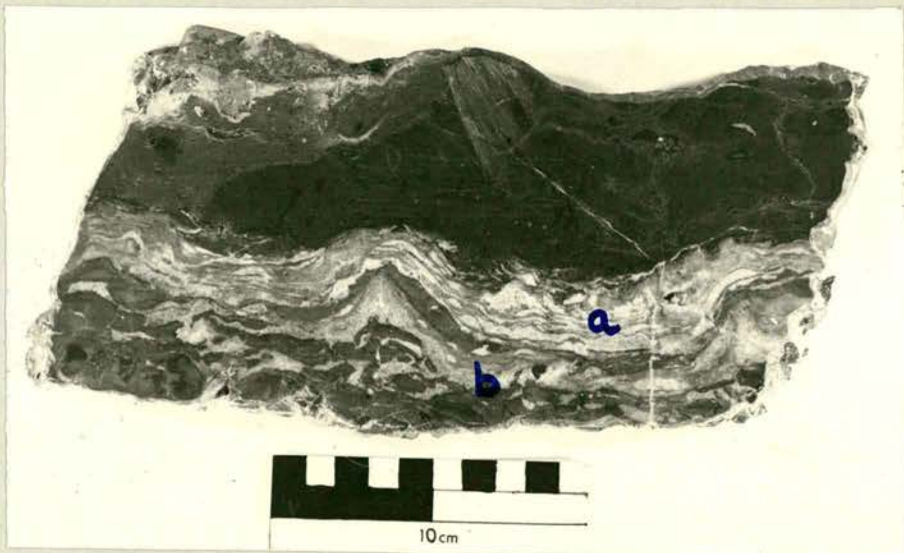


Figure 2

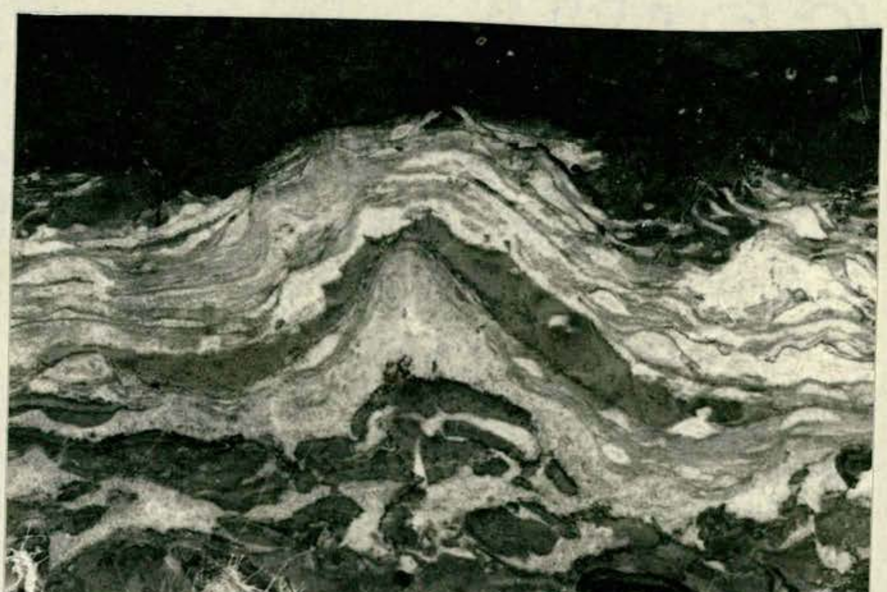


Figure 3

Plate 4:5, Figs. 2 & 3 and Plate 4:6. Within the core recovered from the I.G.S. Benan Burn borehole examples of this microfacies are seen as shown in Appendix II.

Bathurst (1976, p.395) proposed that a bed of limestone be regarded as a hardground "if its upper surface has been bored, corroded (by abrasion) if encrusting or other sessile organisms are attached to the surface, or if pebbles derived from the bed occur in the overlying sediment". Horizons of this type, that originally formed a hard, cemented sea-floor, are well known in the geological record, in rocks ranging in age from Ordovician (Lindstrom, 1963, Palmer, 1977, Palmer and Palmer, 1977) to Recent (Shinn, 1969, Taft et al., 1968, Dravis, 1972). The isotope and trace element geochemistry of carbonate cements in Jurassic limestones interpreted as hardgrounds supports a sub-marine, sediment/water interface origin for these bored and en-crusted horizons (Marshall and Ashton, 1980). The distinctive nature of such deposits when viewed as substrates available for colonisation may give rise to an assemblage of epifaunal and in-faunal elements specially adapted to the exploitation of a hard substrate, examples of various ages have been described by Goldring and Kazmierczak (1974), Baird and Fursich (1975), Bromley (1975) and Palmer and Palmer (1977).

4.2.8 Description of microfacies C horizons

Macroscopic features

All occurrences of microfacies C, seen both in core section and in outcrop display the following features:

(1) Constant thickness of 4-5cm (Appendix II).

(2) Sharp, clearly defined upper surface, which may be planar if not encrusted, Plate 4:6, or may be variably encrusted, Plate 4:5, Fig. 2.

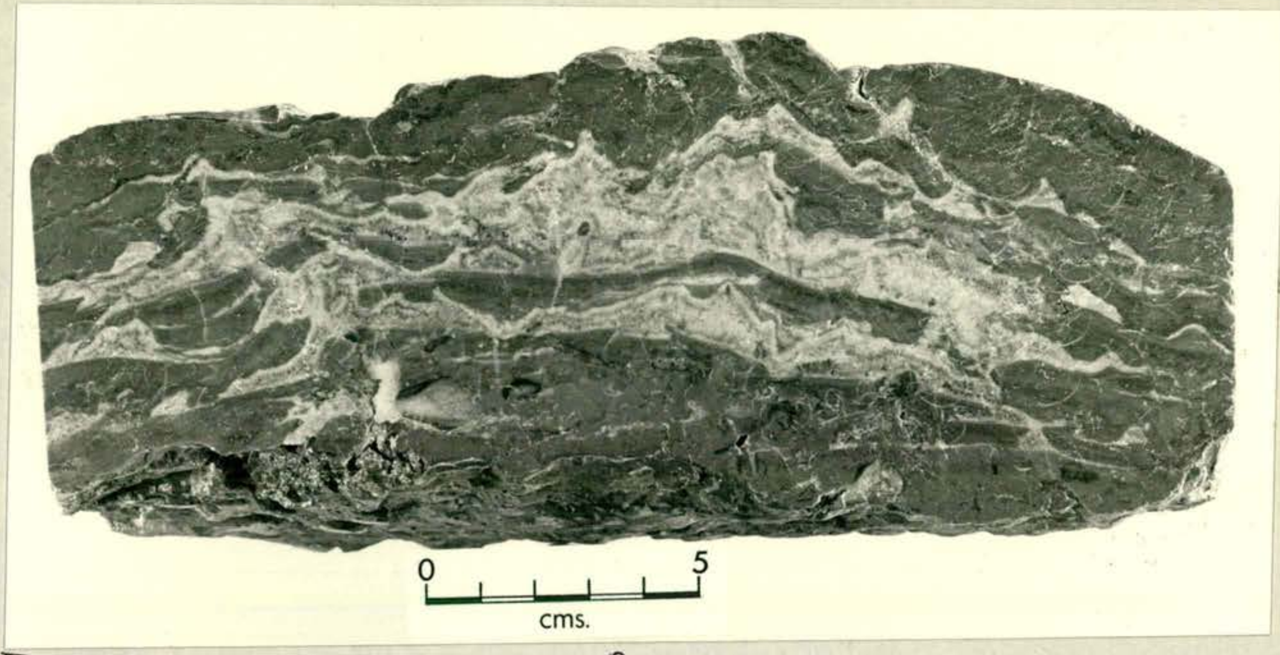
(3) Distinctive pale (Plate 4:6), and noticeably purer carbonate than seen in any other microfacies.

(4) The base of horizon is gradational, uneven, and often rich in coarse grained biogenic grains, Plate 4:6..

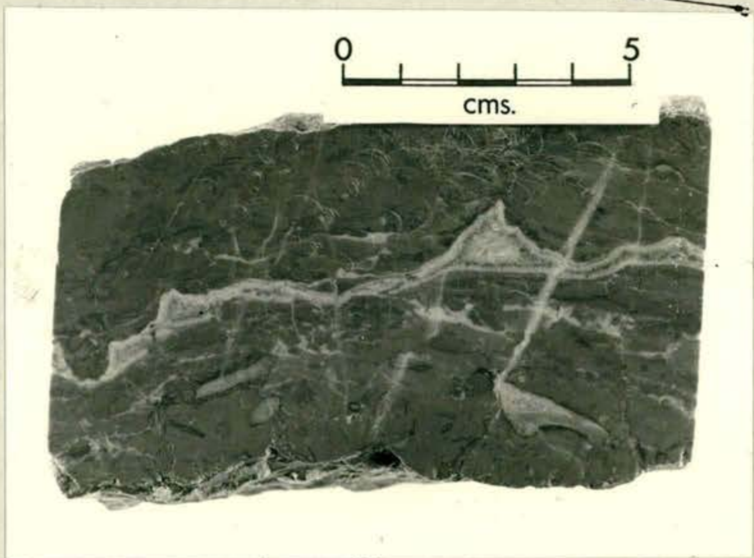
(5) No evidence for extensive bioturbation within any of these horizons.

Plate 4.6

Cut surfaces of a hardground horizon block. The front face (A) shows the multiple development of cavities beneath the cementing horizons. The cavity roofs are, in general, irregular and uneven, whilst cavity floors are more nearly planar. The remaining two faces, the side (B) and near (C) demonstrate the laterally restricted nature and dominantly domal form of the teepee structure.

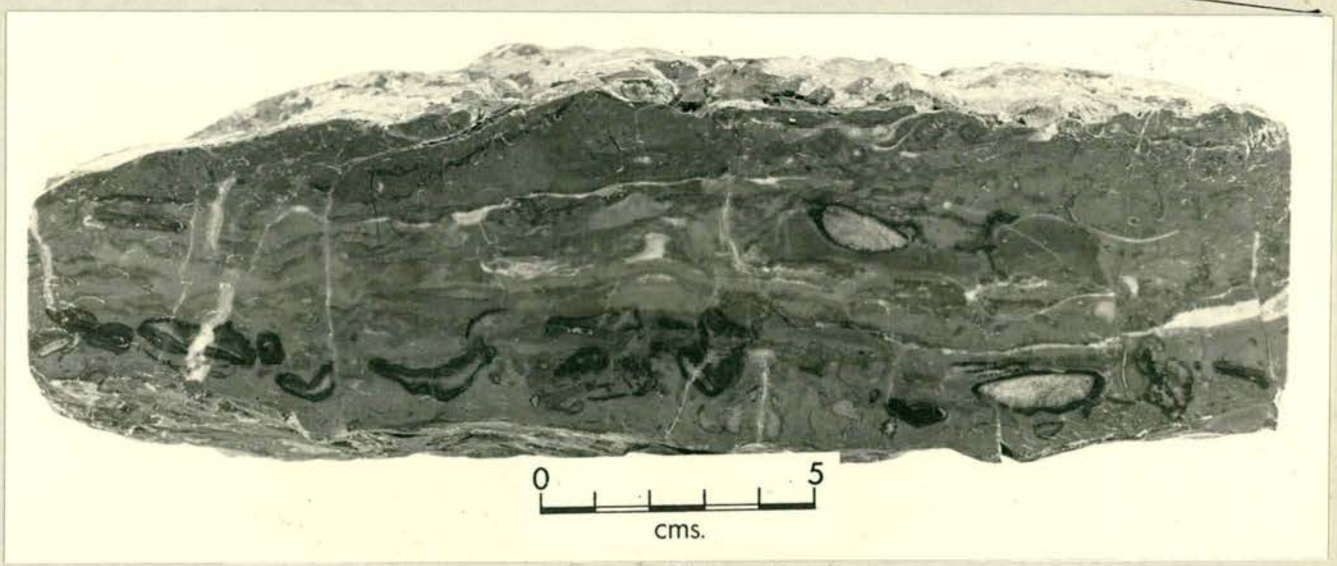


A



B

Plate 4.6



C

(6) Large, domed, cavities infilled with coarse radiaxial-fibrous calcite are present, Plate 4:6 and Plate 4:5, Figs. 2 & 3.

Microscopic Features

The upper surface may be encrusted by either the large organisms shown in Plate 4:5, Figs. 2 & 3 or by small bryozoans, Plate 4:7, Fig. 1. These bryozoans are similar in terms of both size and structure, to the encrusting lamellate bryozoans Prasopora and Hemiphragma, described by Palmer and Palmer (1977) from a Middle Ordovician hardground in the Upper Mississippi Valley. Small stromatoporoids are also present, Plate 4:7, Fig 2.

In addition, botryoidal growths of dusty fibrous calcite similar to fascicular-optic calcite (Kendall, 1973) most probably a neomorphic modification of aragonitic cement fans, Plate 4:7, Fig. 3, is also present in the upper parts of one microfacies C horizon. Closely similar crystal growths have been described by Mazzullo and Cys (1979) and Mazzullo (1980) from Permian phylloid algal mounds in New Mexico, where they are a volumetrically significant mound components. These authors considered the crystals to have grown on a hard sea floor, having been precipitated directly from seawater. A similar origin is proposed for the crystal growths from the Stinchar Valley Formation, although the possibility that they developed in a cavity below the sediment surface cannot be discounted, see caption Plate 4:7, Fig. 3. In terms of their internal features, all microfacies C horizons are similar in that they are composed of dense, algal/peloidal/spicule wackestones showing a variably developed clotted or grumuleuse texture, Plate 4:8, Fig. 1. Non-compacted burrows are common, these are partially infilled with peloidal intraclastic wackestones, the remaining voids being occupied by clear, non-ferroan, calcite cement, Plate 4:8, Fig. 2. Fenestral or birds-eye fabrics occur within the hardgrounds, three types of fenestra being recognisable:

(1) Laminar, laterally extensive voids up to 1mm in depth and several mm across. The void margins are generally parallel to laminae in the peloidal wackestones and also to horizontally cabled clusters of Girvanella filaments, Plate 4:8, Fig. 3 that are interpreted as the remains of stromatolitic algal mats (see section 4.2.20).

Plate 4.7

Figure 1.

Byozoan, either <u>Prasopora</u> or <u>Hemiphragma</u>, encrusting the upper surface of hardground.

Thin section, 26.79m, Benan Burn Borehole, plane polarised light.

Figure 2.

Small stromatoporoid (genus unknown) encrusting the upper surface of hardground. The cemented horizon is notably finer grained and contains less argillaceous material than the overlying calcareous siltstones.

Thin section, 29.25m, Benan Burn Borehole, plane polarised light.

Figure 3.

Botryoidal fans of radiaxial-fibrous calcite developed in cavity within hardground horizon.

Thin section, 29.25m, Benan Burn Borehole, plane polarised light.

Plate 4.7

Figure 1
0.45mm

Figure 2
2mm

Figure 3
0.016mm

Plate 4.8

Figure 1.

'Clotted' or grumuleuse fabric developed in algal/peloidal wackestone of hardground.

Thin section, CB/6/79A, Benan Burn quarry, plane polarised light.

Figure 2.

Irregularly roofed, partially sediment infilled burrow within hardground horizon. The internal sediment is peloidal and the remaining void is occupied by clear, non-fibrous, calcite cement.

Thin section, CB/6/79A, plane polarised light.

Figure 3.

Laminar, laterally extensive, fenestra, running parallel to flat lying filaments of Girvanella.

Thin section, CB/6/79B, plane polarised light.

Plate 4.8

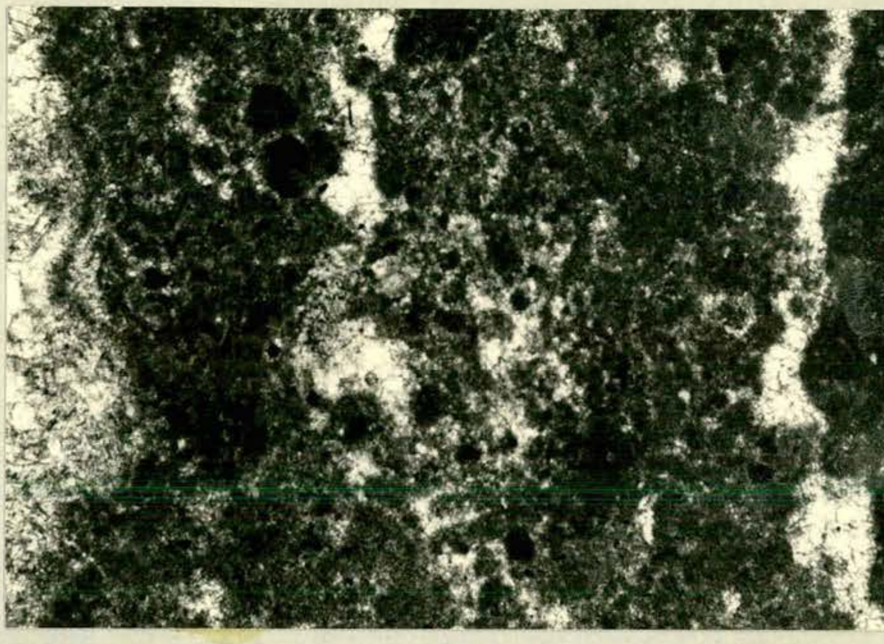


Figure 1

0.45mm

Figure 2

0.45mm

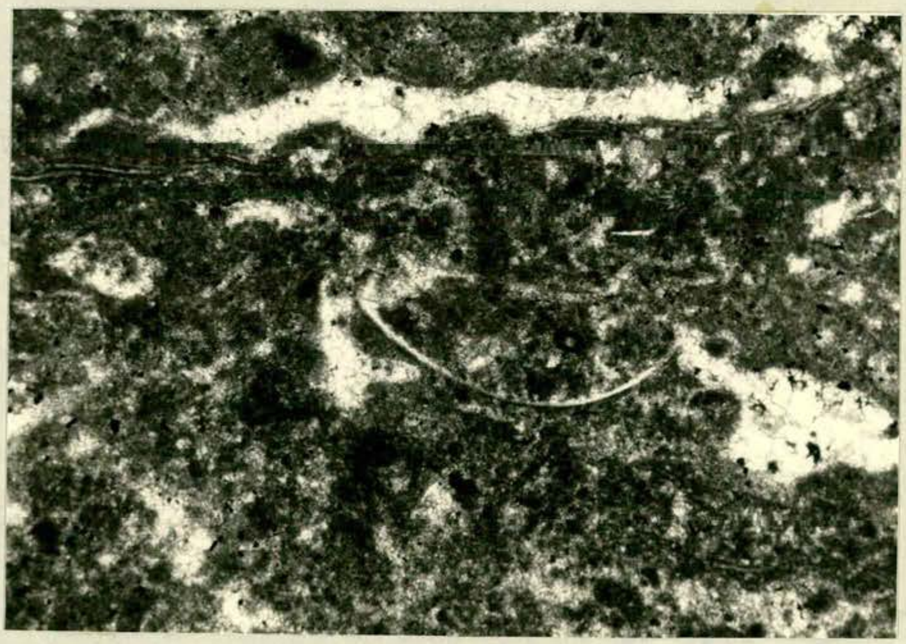


Figure 3

0.2mm

(2) Irregular voids resulting from the activity of burrowing organisms, or from the removal of uncalcified algal filaments, or dewatering, lacking evidence of dissolution, Plate 4:9, Figs. 1 & 2.

(3) Irregular voids clearly resulting from the dissolution of certain areas of the sediment, Plate 4:9, Fig. 3, these fenestrae may contain a partial sediment infilling.

Abundant algal remains, a full description of which is given in section 4.2.19, are a distinctive feature of all microfacies C horizons. In all cases Girvanella is the dominant form, the filaments are seen either as cabling bundles running parallel to the surface of the hard-ground, Plate 4:8, Fig. 3, as skeletal stromatolites (Riding, 1977), or as faint filament outlines seen within the dense, dark, peloidal micrites. Whether microfacies C horizons represent subtidal algal mats or stromatolites is uncertain, but this possibility cannot be discounted for although no stromatolitic, cryptalgal, structures are seen, algal remains are abundant.

The association of fenestral fabrics with algal/peloidal sediments is generally regarded to be indicative of deposition and diagenesis in intertidal, peritidal, very shallow subtidal and particularly supratidal environments (Shinn, 1969, Hagan and Logan, 1974, Logan et al. 1974, Ginsburg, 1975, Grover and Read, 1978). Monty (1976) describes fenestral fabrics developed within subtidal stromatolities from Shark Bay, Australia and Andros Island, Bahamas, the dominant algae within which are members of the family Oscillatoriacae. These algae are uncalcified and it is thought to be the decomposition of filaments within the sediment that gives rise to the cavities later recognised as fenestrae (Monty, 1976, Monty and Hardie, 1976, Logan et al., 1974). It is possible that some of the microfacies C fenestrae may have formed in this manner, certainly, the fenestrae illustrated in Plate 4:9, Fig. 2 bear a very close resemblance to the fenestral filament molds figured by Monty (1976, Fig. 14).

Plate 4.9

Figure 1.

Fenestral fabric developed in hardground horizon. The origin of this particular texture is not certain, although a mechanism involving the removal of non-calcareous algal filaments or growths cannot be discounted Such a texture might, alternatively, form from the entrapment of gas bubbles within the sediment.

Thin section, CB/3/79A, plane polarised light.

Figure 2.

Fenestral fabric originating from the burrowing of a partially lithified lime mud. The burrow roof is irregular, whilst the lower areas are infilled by peloidal sediment.

Thin section, MN/1/79B, plane polarised light.

Figure 3.

Detail of fenestra margin, showing dissolution of lime mudstone and also of the body wall and internal cement of a gastropod. The resulting porosity is infilled by both microspar and also a small amount of peloidal sediment.

Thin section, MN/1/79A, plane polarised light.

Plate 4.9

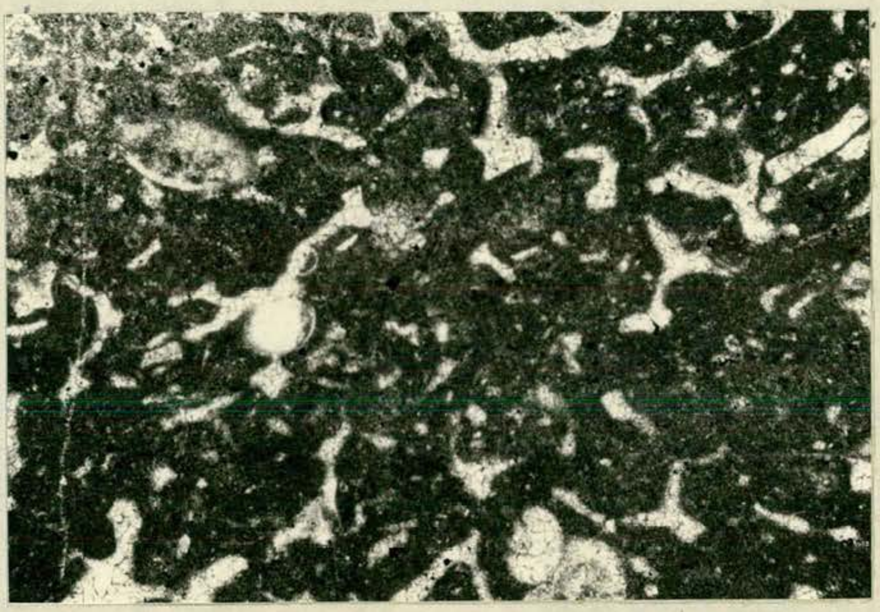


Figure 1
0.5mm

Figure 2
0.25mm

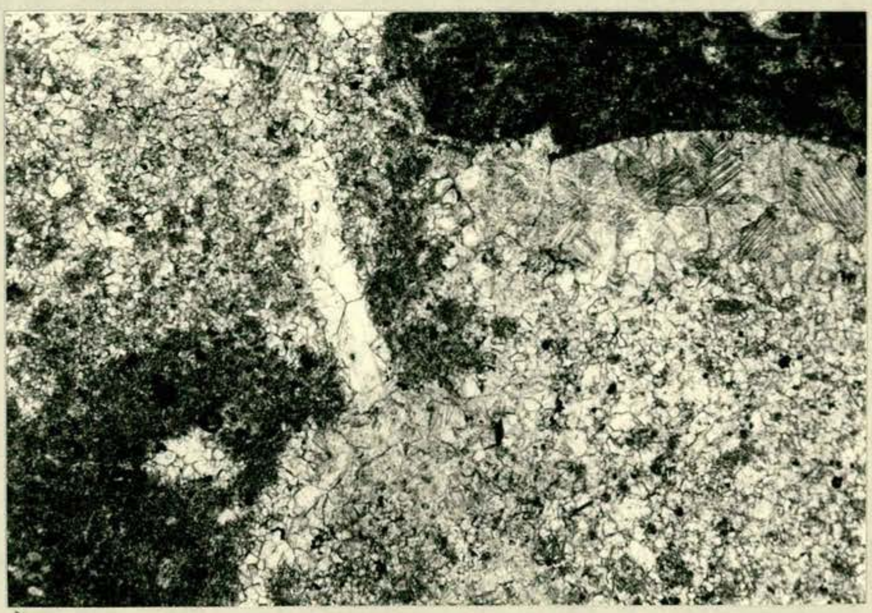


Figure 3
0.5mm

4.2.9 Teepee structures

The early lithification of carbonate sediments, necessary for a hardground horizon to form, involves expansion of the affected layer due to the force of crystallisation (Shinn, 1969). Buckled, antiform, teepee structures (Adams and Frenzel, 1950) thought to result from the early lithification and expansion of carbonate sediments in peritidal zones have been described by Assereto and Kendall (1977). Cavities formed within the teepees by the upward buckling of the cementing layer may be either partially or wholly infilled with internal sediment or calcite spar, often of marine origin. This mode of formation is loosely similar to that proposed by Bathurst (1980, 1982) for stromatactis cavities in Ordovician, Devonian and Carboniferous carbonate mudmounds. Bathurst does not, however, consider upward doming of cementing horixons as a means of cavity formation, preferring instead a process of submarine, physical and biogenic erosion below the lithified horizon.

Within the Stinchar Valley Member certain microfacies C bed-horizons contain laterally discontinuous, antiformal, cross-cutting bands of non-ferroan calcite spar, Plate 4:6, that in overall morphology and internal fabric, closely resemble both teepee and stromatactis cavities. These spar filled cavities cut across the algal and peloidal laminae, and may contain small amounts of geopetal internal sediment, Plate 4:6 and Plate 4:11, Fig. 1. Cavity roofs are often scalloped and may be sharply defined and/or encrusted by structures thought to be organic, perhaps algal in origin, Plate 4:10, Figs. 1 & 2. Cavity floors are generally planar and are not seen to be encrusted. Alteration of cavity floors is common-place, the degree of neomorphic alteration of the wackestones increasing towards the cavities, Plate 4:11, Fig. 1. Similar alteration of lime-muds to sparry calcite in areas adjacent to an open cavity system is reported by Ross et al. (1975), from stromatactis type cavities developed in the core facies of a Middle Ordovician mud mound at Meiklejohn Peak, Southern Nevada. In the above example, aggrading neomorphism (Folk, 1965) was thought to be the process by which the micritic limestone was converted to a coarser crystalline mosaic. The same process is thought to have been responsible for alteration of the microfacies C wackestones, in some cases completely obliterating primary fabrics, Plate 4:11, Fig. 2.

Plate 4.10

Figure 1.
Micritic laminae, perhaps of algal origin, developed on successive generations of faintly fibrous, botryoidal, calcite cements, roof of teepee cavity.
Thin section, MN/1/79A, plane polarised light.

Figure 2.
Detail of teepee cavity, showing dense, dark, micrite, laminae, both on the cavity roof (a) and also on subsequent cement fans (b). The inner areas of the cavity are infilled by heavily neomorphosed calcite spar.
Thin section, MN/1/79A, plane polarised light.

Figure 3.
Central area of teepee cavity showing coarse radiaxial fibrous, inclusion rich, calcite, and final cement fill of clear calcite spar.
Thin section, CB/3/79A, plane polarised light.

Plate 4.10

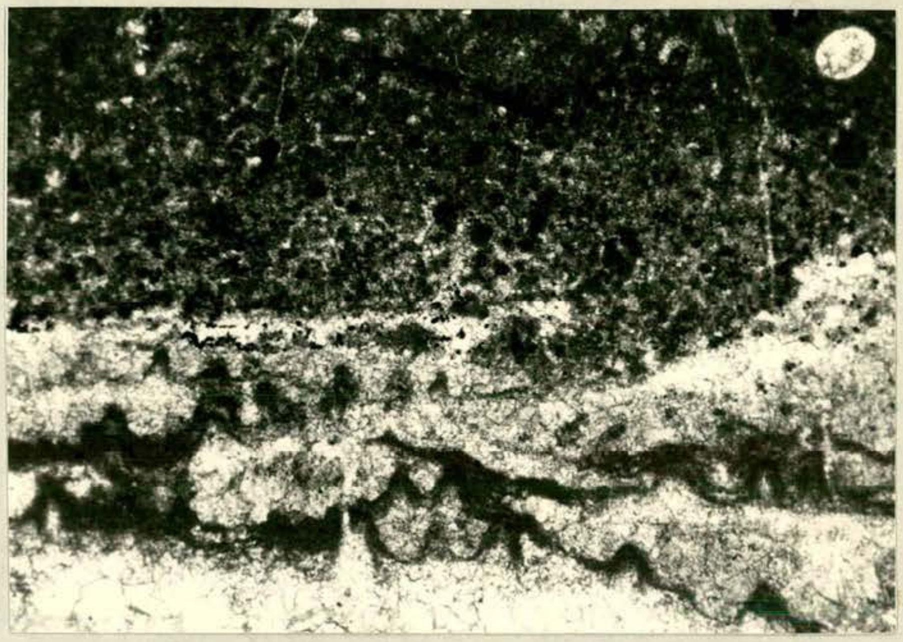


Figure 1

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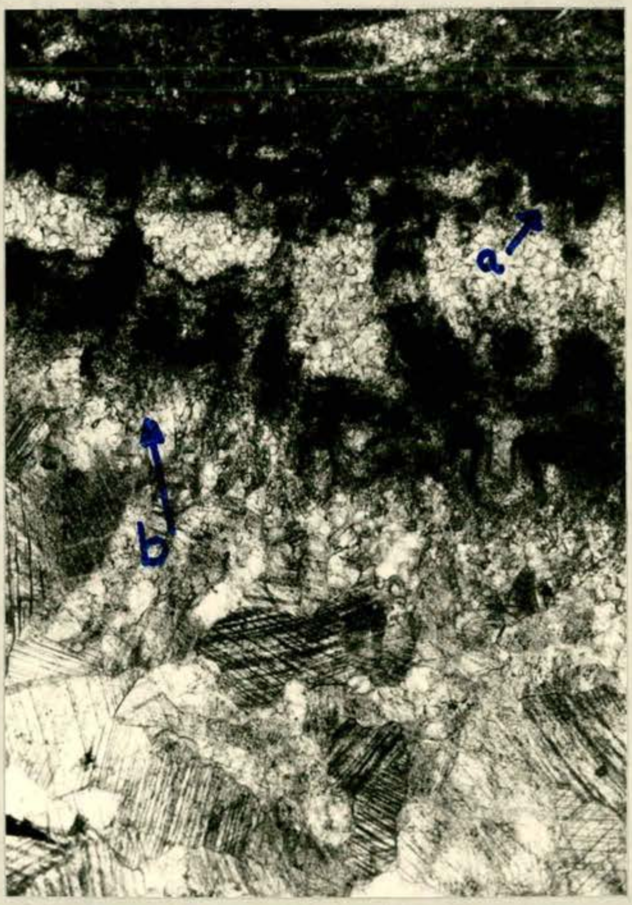


Figure 2

0.5mm

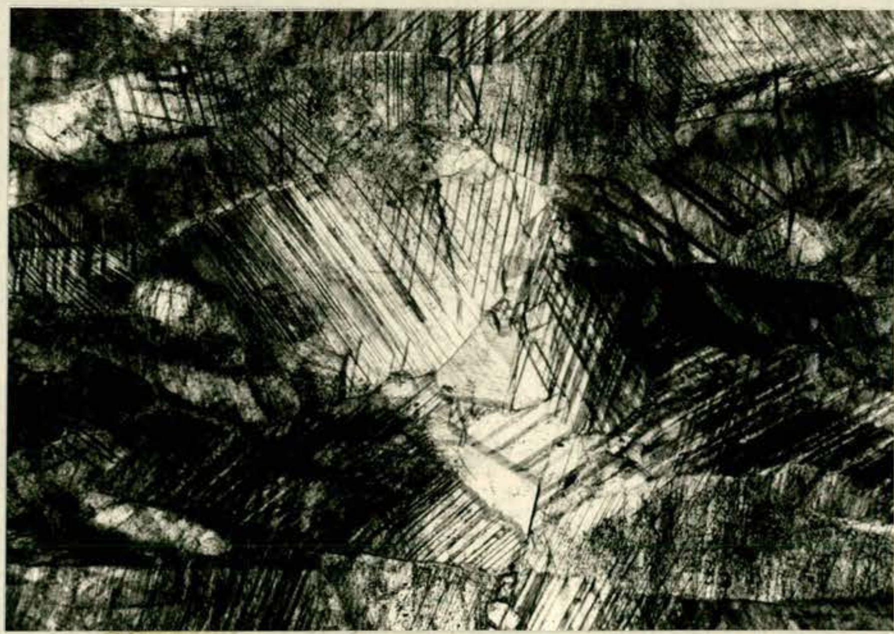


Figure 3

0.4mm

Plate 4.11

Figure 1.
Well defined floor to teepee cavity, showing neomorphism of the original sediment and the growth of coarse radiaxial fibrous spar.
Thin section, CB/3/79A, plane polarised light.

Figure 2.
Extensively neomorphosed fenestral wackestone forming the floor of a teepee cavity. The degree of alteration is progressive and shows how a clotted or grumuleuse fabric may be produced as a result of neomorphic processes.
Thin section, CB/3/79A, plane polarised light.

Plate 4.11

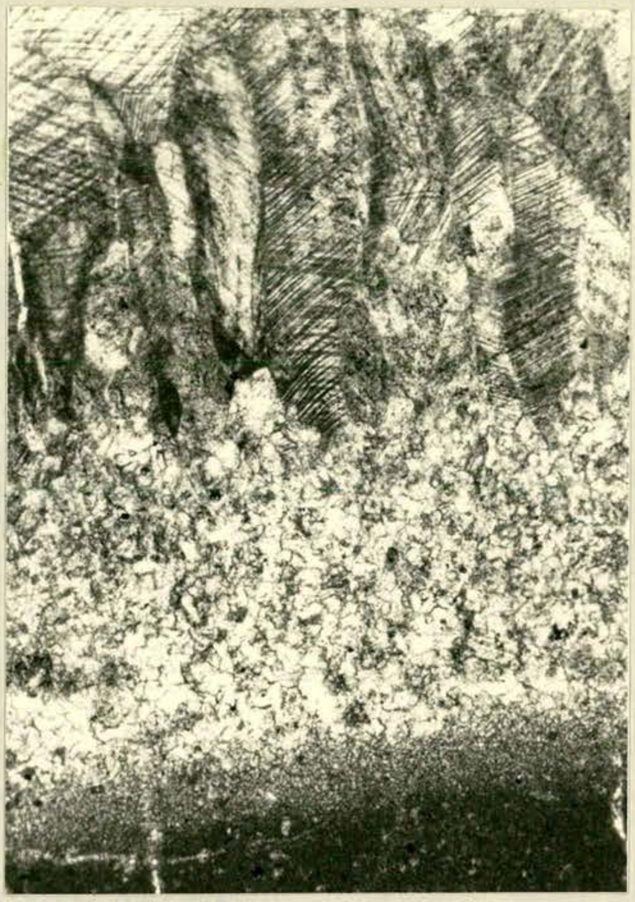


Figure 1

0.5mm

Figure 2

0.5mm

Whilst certain of the undulose micritic laminae occurring on cavity roofs and interpreted as being of either algal or perhaps fungal origin developed on a substrate of algal wackestone, others may have originated as encrustations on a substrate of cavity filling, formerly fibrous aragonite cement, Plate 4:10, Figs. 1 & 2. If this interpretation is correct, these features are closely comparable in terms of origin as well as appearance to the micrite laminae within sub-sea fibrous aragonite cement fans, described by Mazzullo and Cys (1979) from Permian phylloid algal mounds in the Sacramento Mountains, New Mexico. These authors used the inferred presence of algae as an indication that the aragonite botryoids grew on the sea floor. In the present case the small fans of carbonate cement are also thought to have been precipitated from sea-water. The main cement type in filling the cavities is coarse radiaxial-fibrous calcite, Plate 4:10, Fig. 3, Plate 4:11, Fig. 1, the end result of neomorphic alteration of a fibrous, seawater derived carbonate cement (Kendall and Tucker, 1973, Bathurst, 1977, Mazzullo and Cys, 1979). Towards the centres of the cavities the spar often becomes clear, non-radiaxial-fibrous, and sometimes blocky, Plate 4:10, Fig. 3, perhaps indicating the presence of a later non-marine cement generation.

The final voids in larger cavities may be infilled with a coarsely crystalline quartz, Plate 4:12, Fig. 2. Nodules of black chert, up to 4cm in diameter, occur in or beneath the hardground horizons, they are, however, highly fractured and could not be examined in thin section. The origin of the silica is uncertain, the most likely source is siliceous sponge spicules, which undergo dissolution, redistribution and precipitation in available voids. This process has been proposed by Meyers (1977) to explain the chertification of Mississippian limestones in the Lake Valley Formation in New Mexico, where silica occurs both as a replacement of calcite and as a void filling cement. Furthermore Meyers suggests that the apparent facies control over chert distribution in the Lake Valley Formation is a function of the initial distribution of sponge spicules, which would appear to have been locally abundant.

In the microfacies C horizons, however, there is little evidence for the former existence of abundant sponge spicules. The replacive micro-quartz aggregates most probably represent a late

Plate 4.12

Figure 1.
Late stage quartz cement in the porosity remaining after the growth of coarse calcite spar.
Thin section, CB/6/79A, plane polarised light.

Figure 2.
Microcrystalline quartz cement (a) replacing neomorphosed radiaxial fibrous calcite spar.
Thin section, MN/1/79A, plane polarised light.

Plate 4.12

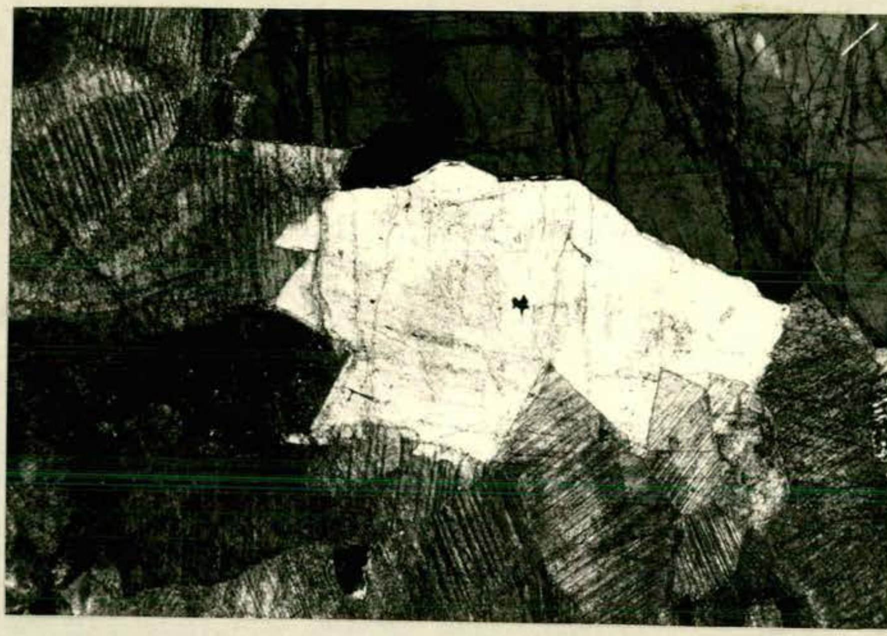


Figure 1

0.1mm

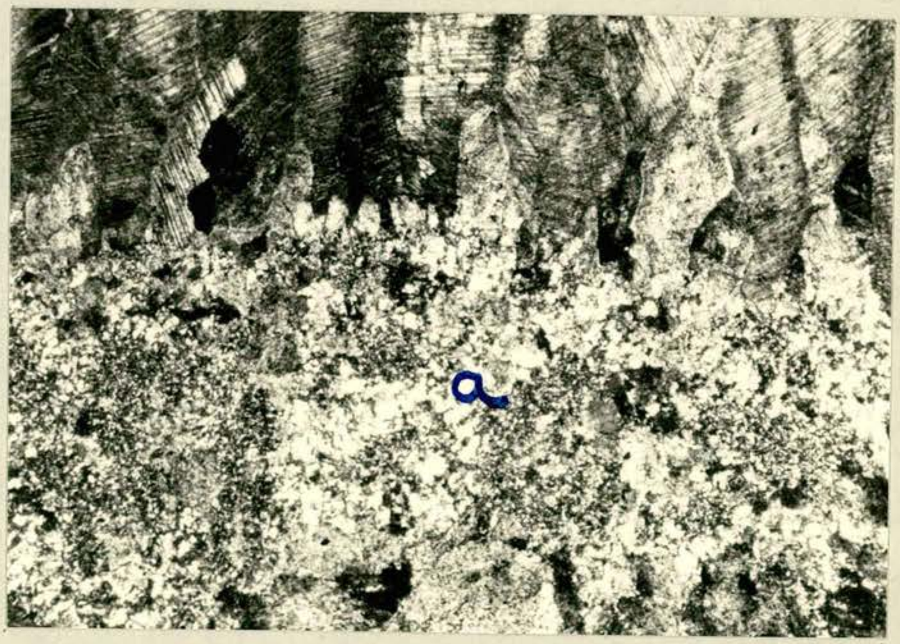


Figure 2

0.25mm

diagenetic event, possibly related to burial and compaction, this is indicated by the association of this mineral habit with fine fracture systems, Plate 4:12, Fig. 2. The origin of the nodular chert cannot be determined but it is possible that they are of primary origin, deposited more or less contemporaneously with the carbonate in the manner suggested by Orme, (1974), for nodular cherts in the Visean limestones of Derbyshire.

4.2.10 Conclusions

In summary the microfacies C horizons are interpreted as submarine hardgrounds, produced by the early lithification of algal/peloidal lime muds. Cementation was accomplished by the precipitation of carbonate cements directly from seawater, perhaps during a period of markedly reduced sedimentation (see section 4.2.14). Lateral expansion of the horizon undergoing cementation resulted from the crystallisation force of the carbonate cements within the lime muds, and resulted in the formation of teepee or stromatactis like cavities. These cavities are infilled by radiaxial-fibrous calcite, thought to represent a diagenetic modification of a fibrous marine cement. Later diagenetic events include the infilling of residual porosity by clear, in places blocky, calcite spar and/or silica.

4.2.11 The origins of nodularity in carbonate sediments

Discussion

Nodularity is a commonplace feature of carbonate rocks, yet there is, remarkably, little information in the literature dealing with the mechanism or mechanisms by which this particular feature may form. The following broad theories regarding the genesis of nodules can be recognised among the papers so far published.

(1) Concretionary: nodules form by a diagenetic segregation of carbonate and non-carbonate materials (Illies, 1949, Hallam, 1964, Kukal, 1969, Tucker, 1973, Jenkyns, 1974). The latter three authors propose that this may be accomplished by the solution of fine grained carbonate and its reprecipitation as horizons of nodules at shallow depths below the sediment surface. Schindewolf (1921), Weeks (1953) and Berner (1968), suggest that the bacterial decay of organic remains may be responsible for initiating the early diagenetic precipitation of calcite in discrete nodules as a result of locally modified pH conditions.

(2) Early cementation: at or just below the sediment surface. Noble and Howells (1974), Jones et al. (1979) and Mullins et al. (1980) provide evidence that certain nodular limestones formed as a result of the early lithification of carbonate sediment at or near the sediment surface. Campos and Hallam (1979) conclude from a study of the oxygen and carbon isotopes in certain Jurassic nodular limestones, that in some cases the carbonate cements within the nodules were most probably derived from seawater, no diagenetic reduction in O^{18} having taken place. During an investigation of Holocene carbonate environments in the Persian Gulf, Shin (1969), and Taylor and Illing (1969) record lithified crusts and nodules formed at or within a few centimetres of the sediment surface. Isotopic evidence from the cements in these hard layers studied by Shinn indicate direct precipitation from supersaline seawater (Lloyd, 1964). All the above authors conclude that sedimentation rate may exert a significant control over the early precipitation of cements derived directly from seawater.

The distinction between this and the previous category is rather vague and a degree of overlap is probable. Raiswell (1971) describes discrete concretions of Liassic age that formed as a result of early cementation, this being permitted by a pause in sedimentation.

(3) Tectonic: nodules form by the breakage and separation of continuous carbonate layers (Born,1912, Falke, 1949, Richter, 1965). Although non-tectonic in nature the "sedimentary boudinage" of McCrossan (1958) (Nichols, 1966, Wobber, 1966, Jameson, 1980) is included in this category. The differential compaction of an alternating sequence, and the lateral spreading of a given bed is the basic feature of both processes.

(4) Pressure solution: Wanless (1979) suggests that the formation of nodular limestones in general is solely the result of pressure solution processes. This conclusion centres around the author's observation that many carbonate nodules or concretions have microstylolite swarms around their margins. This, however, fails to take into account that microstylolites may be a modifying rather than a casual agent in the genesis of nodular limestones, although it is possible that certain examples may have formed in this fashion.

(5) Burrow traces: Fursich (1972) and Abed and Schneider (1981) conclude that Thalassinoides and similar burrows of probable calliannassid, crustacean affinities (Shinn, 1968) exert a primary control over the development of nodularity. The presence of mucus or organic material in the burrow lining is postulated as a means of initiating the early precipitation of carbonate cements in these areas.

A more complex sequence of events involving a number of differing processes and leading to the formation of nodules in deep water, peri-platform carbonates on slopes off the Bahamas is proposed by Mullins et al. (1980). In this instance resedimented and pelagic carbonates are winnowed by bottom currents, active at water depths of around 400m, thereby facilitating lithification and precipitation of high Mg calcite cements as a result of enhanced permeability and increased circulation of interstitial pore waters. Subsequent biogenic and physical reworking produce silt to gravel sized grain-supported intraclastic grainstones. Continued cementation produces nodules, decreased current velocities allow the deposition of pelagic muds and vertical mixing by burrowing organisms results in the final 'floating' fabric. Whilst a fuller explanation for the frequent changes in current velocity, that are so critical to this hypothesis, would strengthen the model, the account given provides definite evidence for the importance of sedimentation rate and bioturbation in controlling the formation of nodular limestones and the precipitation of carbonate cements.

4.2.12 Observational evidence from the Stinchar Valley Member

Study of the nodularity in microfacies A horizons of the Stinchar Valley Member was carried out using core recovered from the I.G.S. Benan Burn Borehole. Samples were examined in thin section, as polished, oiled or methylene blue stained surfaces. Core material was generally used in preference to samples collected from natural exposures, features in the silty clay interbeds being better preserved. The observations felt to be important in understanding the ways in which nodularity may have developed are listed below.

(1) The presence of relatively rare uncompacted, dominantly horizontal, chondritiform, burrow systems in the nodules, the more abundant burrows in the silty clay interbeds are deformed around the nodules, Plate 4:13, Fig. 3.

(2) Avoidance of nodules by burrowing organisms, Plate 4:13, Figs. 1 & 2, and caption.

(3) The presence of large, non-compacted, carbonate-walled burrow systems, around which burrow traces in the surrounding silts are deformed, Plate 4:14, Fig. 1.

(4) The presence in microfacies C of intraclasts presumed to have been exhumed and transported, as resistant sedimentary particles, see section

(5) Non-nodular horizons are markedly more heavily bioturbated, as shown by burrow density, Plate 4:5, Fig. 1.

(6) Depth of bioturbation was probably no more than 5cm at a maximum, Plate 4:16, Fig. 2, and caption.

On the basis of these observations the following conclusions may be derived:

(1) Nodules became lithified at or within a few centimetres of the sediment surface but were prevented from developing into hardgrounds by the influx of clastic detritus. They were sufficiently hardened to present an obstacle to burrowing organisms, and to withstand exhumation and transportation during extreme storm events.

(2) Bioturbation by relatively small organisms inhibits the development of nodularity, either by admixture of the clay and carbonate fractions or by some other aspect of the bioturbation process.

(3) Certain burrowing organisms may have actively promoted the formation of a hard or firm, carbonate, burrow wall, Plate 4:14, Fig. 1. This may have resulted from the rapid precipitation of carbonate in the burrow wall perhaps promoted by the presence of organic material in the manner outlined in section 4.2.19.

In addition to the above observations there would seem to be a continuous gradation between microfacies A, B & C. This may indicate that variations in a common casual factor or factors are responsible for the development of the different microfacies. Any explanation for the genesis of nodularity may also, therefore, have to account for the origins of non-nodular horizons.

Plate 4.13

Figure 1.

Cut surface of core (Left hand side of photograph is up) showing avoidance of carbonate nodules by burrowing organisms. The uppermost part of the interval constitutes the base of a thin sheet sandstone unit, burrows (arrowed) penetrated through the base of the sand and are infilled with this same material. These distinctive burrow traces do not penetrate the carbonate nodules and in places appear to follow a nodule margin (b).

Benan Burn Borehole, 78.65m.

Figure 2.

Base of thin sheet sandstone penetrated by sand infilled burrows (a), which, as in the previous instance, are seen to avoid the carbonate nodules, passing between the two nodules (b) and into the underlying silty interbed (arrowed).

Benan Burn Borehole, 45.24m.

Figure 3.

Cut surface of core, showing deformation of burrow traces in silty interbeds around the carbonate nodules, which show no signs of compaction.

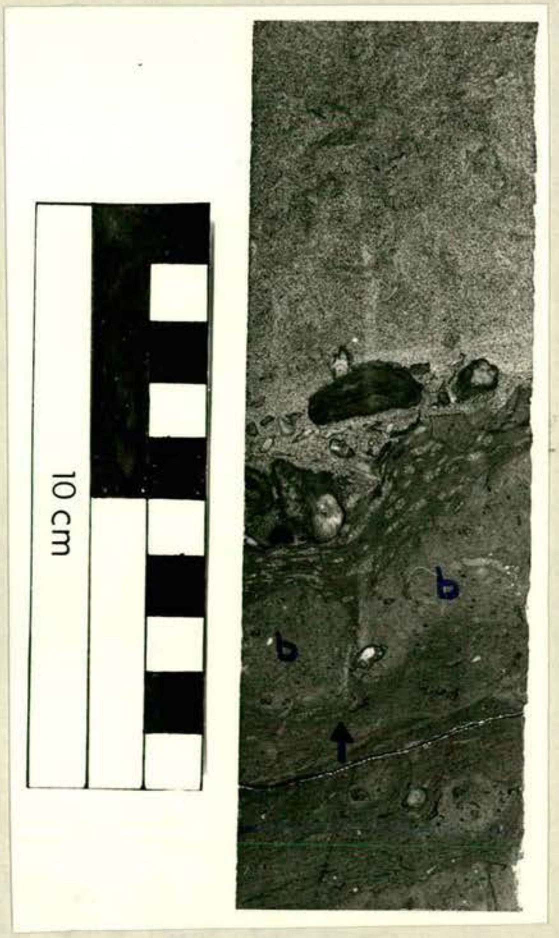
Benan Burn Borehole, 29.25m.

Plate 4.13

Figure 1

Figure 2

Figure 3



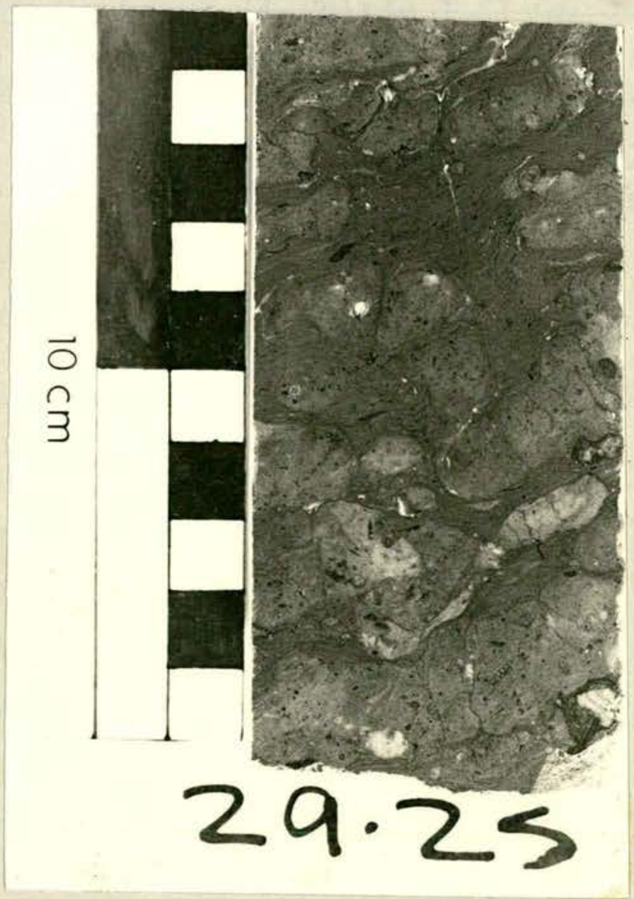


Plate 4.14

Figure 1.
Carbonate nodules whose origin is related to the activity of burrowing organisms. The nodules formed as hollow 'tubes' whose walls were rapidly cemented by carbonate. Internal voids are infilled by sediment (a), and also two generations of calcite cement (b and c).
Core surface 29.95m, Benan Burn Borehole.

Figures 2 and 3.
Extensive bioturbation seen in non-nodular (microfacies B) horizons, the burrow traces are chondritiform.
Figure 2, Benan Burn Borehole, 45.12m.
Figure 3, Benan Burn Borehole, 70.44m.

Plate 4.14

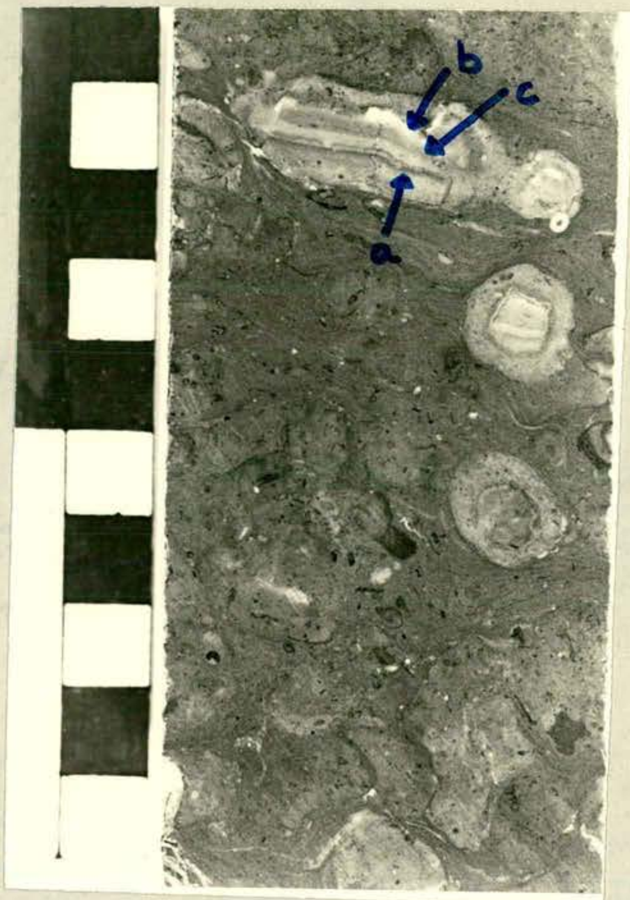


Figure 1

Figure 2

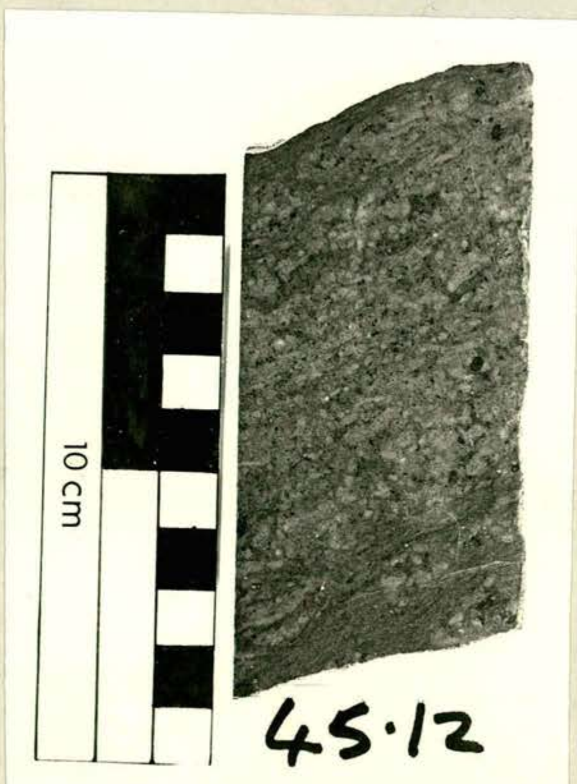


Figure 3

4.2.13 Discussion

In the author's opinion the evidence presented in the previous section firmly indicates that early lithification was important in the formation of carbonate nodules in the Stinchar Limestone Formation. The more fundamental question of the factors that determine whether or not nodularity is developed still remains.

Workers who have favoured an early diagenetic origin for ancient carbonate nodules have emphasised the importance of the following factors:

i) Sedimentation rates.
ii) Original nature of the sediment
iii) The degree of early lithification
iv) Supersaturation of pore waters with respect to calcium carbonate.
v) Presence of suitable substrates for the nucleation of carbonate crystals.
vi) The presence of clay minerals, to promote carbonate precipitation by adsorbing Mg^{2+} ions.

Shinn (1969) concludes that rapid sedimentation inhibits the early diagenetic cementation of present day shallow water carbonate horizons in the Red Sea. Noble and Howells (1974) and Jones et al. (1979) mention the possibility that nodular limestones may represent incipient hardgrounds. This suggestion is consistent with the conclusion of many authors (summarised in Bathurst, 1976) that true hardgrounds represent periods of non-deposition or only minor sediment accumulation. Within the Stinchar Valley Member the continuum of bedding types/microfacies, from hardgrounds, through nodular limestones to non-nodular, bedded horizons may reflect, at least in part, differing sedimentation rates, and concomitant variations in the rate and degree of early cementation. The original nature of the sediment is important in that an alternating limestone-shale sequence would seem to be necessary to provide the compositional contrast between nodules and matrix. The clays act as a matrix to the carbonate nodules, and may be of importance in diagenesis, although the suggestion of Noble and Howells (1974) that Mg^{2+} may be taken up by clay minerals is thought to be improbable, those that are capable of adsorbing magnesium would probably do so on entering marine waters, and would not therefore be active during diagenesis.

The extent to which early lithification proceeds is of obvious importance in determining whether or not nodularity is developed. The presence of suitable substrates for carbonate nucleation will be important in two respects, in determining the initial sites of cement, and the subsequent growth of the nodule. The lack of suitable substrates in the silty clay matrix may provide a limiting factor on nodule growth.

Pore water chemistry will control whether or not calcium carbonate is precipitated. Hydrogen ion concentration is the controlling variable as shallow marine waters are normally assumed to be supersaturated with regard to $CaCO_3$ (Bathurst, 1976).

Factors not mentioned by previous authors but possibly of significance are:

i) Presence of organic material within the sediment. The work of Weeks (1952), Mitterer (1971), Fursich (1972) and Berner (1968, 1971) demonstrates that the metabolic activity of bacteria involved in the breakdown of organic material within the sediment favours the precipitation of calcium carbonate. Cementation occurs within the zone of active precipitation, which is 5-50cm below the present day surface of the Persian Gulf (Bathurst, 1976).
ii) Bioturbation may alter the pore water chemistry, if it is intense, resulting in undersaturation with respect to $CaCO_3$, Aller (1982), and it may thus prevent cement precipitation. Shallow burrowing around nodules during their formation may also prevent the lateral coalescence by introducing clay rich sediment into areas of uncemented carbonate.

4.2.14 Model for the development of nodularity in the Stinchar Valley Member

The model outlined does not include those nodules clearly related to the burrow systems in Plate 4:14, Fig. 1. These are thought to have formed in the same manner as outlined by Fursich (1973) for similar burrows of Thallassinoid affinity. Fursich considered that early diagenetic nucleation of $CaCo_3$ in the burrow lining took place as a result of a high concentration of mucus or other organic matter in these areas. As the formation of this type of nodule is clearly related to the activity of an organism, the controls proposed for other nodules do not apply.

(1) Deposition of a sequence of moderately pure lime-muds, alternating with carbonate-poor silty muds.

(2) Modification of carbonate and non-carbonate distribution within the upper 5cm of the sediment subsurface by shallow burrowing organisms. This process is synchronous with:

(3) Lithification of areas of carbonate-rich sediment. The extent to which this process proceeds is thought to be dependent on three interacting and partially interrelated factors:

i) Rate of sedimentation; the marine waters from which cement precipitates are only able to penetrate a few centimetres below the sediment surface. Thus if sedimentation rates are high this zone, the zone of active precipitation, will move upwards, limiting the time available for cementation at a given level.

ii) Bioturbation; the activity of burrowing organisms may result in:

(a) Separation of incipient carbonate nodules by introduction of non-carbonate material into intervening areas.

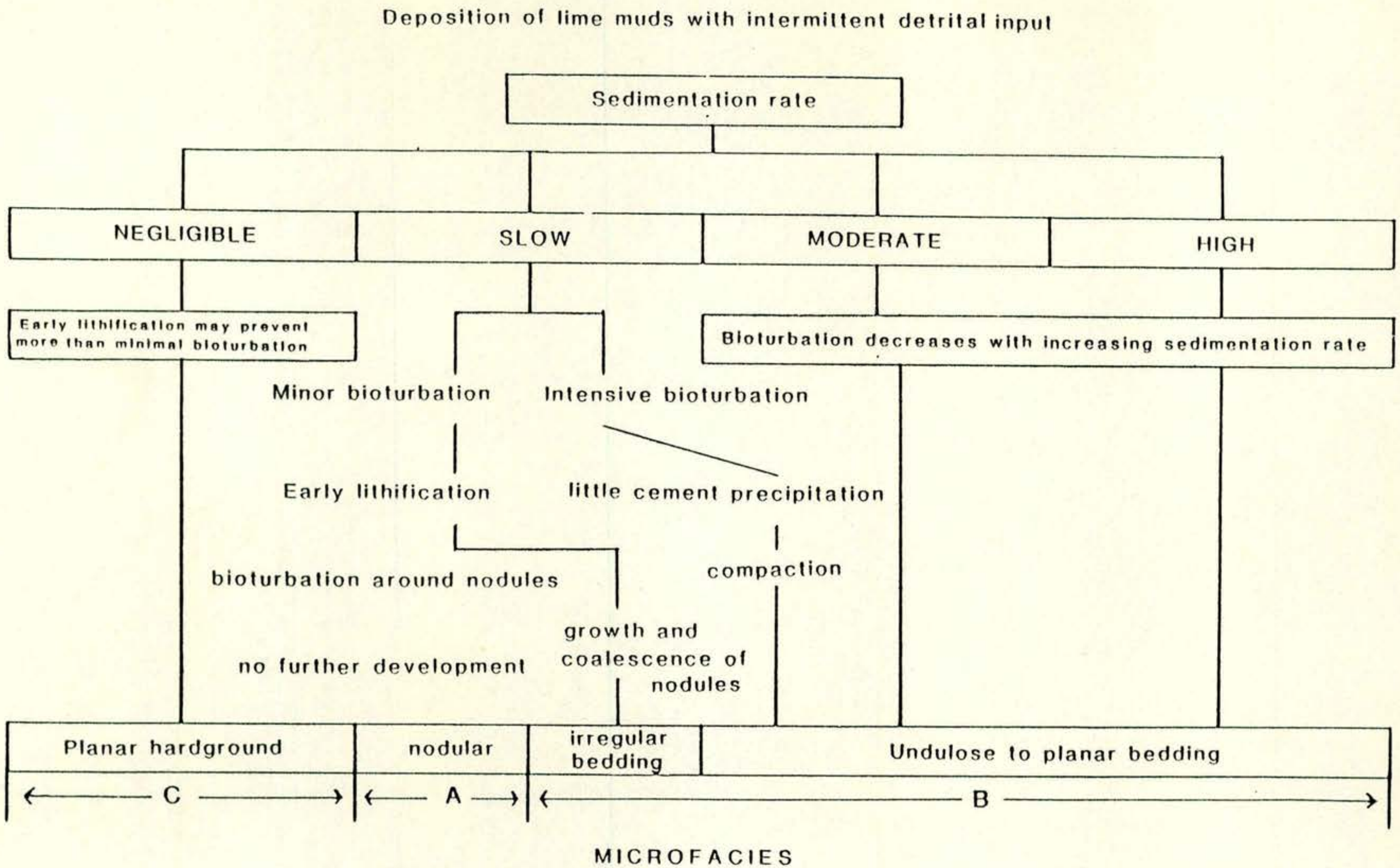
(b) Burial of incipient nodules to levels below the zone of cement precipitation.

(c) Local variations in pH, as outlined by Aller (1982). If pre-lithification burrowing is intensive then the general pH conditions produced may result in undersaturated pore waters, dissolution of carbonate and no early lithification. Once lithification has commenced the process outlined in (a) comes into operation.

iii) Rate of lithification; dependent on porosity, permeability of the unlithified sediment and the way in which this is modified as cementation progresses. The effect of organic matter in increasing the rate of cement precipitation is an unknown factor, but may well have been significant. Within the Stinchar Valley Member the presence of authigenic pyrite, as outlined in section 4.2.18 indicates the former presence of organic material.

Figure 4.2

Simplified model for the development of nodularity in the Stinchar Valley Member



(4) Burial, compaction and dewatering of clay-rich sediments, possibly liberating significant volumes of fluid capable of precipitating cements (Powers, 1967). There is, however no evidence of the late stage, ferroan calcite cements, thought to result from dewatering and iron loss from clay minerals, a process thought by Oldershaw and Scoffin (1967) to have occurred in the Wenlock and Halkyn Mountain Limestones.

Horizons or areas that remained less well cemented, whilst near the sediment surface may undergo compaction. As a result they may behave in a plastic fashion and spread laterally, in a manner similar to the sedimentary boudinage of McCrossan (1958) although there is no conclusive evidence for any such process in the Stinchar Valley Member.

(5) Deformation, resulting in stylolitization around nodule margins, accentuating pre-existing fabrics.

With so many variable factors that may be critical to the formation of nodular limestones, it is obvious that their genesis reflects a rather uniquely balanced set of depositional and post-depositional conditions. Fluctuations in any of the variables may result in the formation of lithologies other than nodular limestone. Figure 4:2 summarises the factors thought to be responsible for the formation of microfacies A, B and C. Sedimentation rate is believed to be the primary controlling factor, with bioturbation playing an important role at low sedimentation rates. As far as can be determined, pressure solution processes were not involved in the initial development of nodularity.

4.2.15 Microfacies D

This microfacies is a bedded, intraclastic-bioclastic packstone seen only at one locality within the Stinchar Valley Member, in the bed of Kirdoninae burn (NX29 254 921) where it forms a laterally untraceable, 10-15cm thick horizon, 6-7 metres below the top of the Stinchar Limestone Formation. A wide variety of grain types is present within a matrix of silty fine sand, identical to that seen in the sheet sandstones that occur in the Stinchar Valley Member, see section 4.2.16. The grains present can be divided into two main categories:

(a) Bioclastic grains, lacking any adhering micritic matrix, Plate 4:15, Figs. 1 & 2.

i) Echinoderm debris, abraided grains with thin micrite envelopes.

ii) Broken gastropod debris with variably developed algal coatings, Plate 4:15, Fig. 2. Thick coatings consist of a number of uneven, variably developed growth phases, both filamentous and non-filamentous algae are present. Lightly encrusted grains are often colonised on one side only.

iii) Broken trilobite debris, the remains of exuvae or dead individuals, most probably fragmented during transportation.

iv) Abraided fragments of Nuia.

v) Skeletal oncolites of Girvanella, Plate 4:15, Fig. 2.

(b) Intraclasts, grains up to 1cm in size, the category includes:

i) Intraclasts where the clast margins are not bounded by a fossil, the features of this group are as follows:

1. Skeletal grains within the intraclasts are sometimes broken across at the clast margin, Plate 4:15, Fig. 1. This indicates that the clasts were transported in a relatively turbulent environment, and lithification was sufficiently advanced to prevent the plucking out of the fossil fragments.

2. The situation outlined above is not always the case and particularly robust skeletal grains may protrude from the intraclast margins, Plate 4:15, Fig. 4. This may give a further indication of the state of the lime mud, suggesting that perhaps cementation may not have been particularly advanced, and that the matrix had less resistance to abrasion than the skeletal grains.

3. Certain broken skeletal fragments are infilled with the silty fine sand that forms the matrix to the intraclasts, Plate 4:15, Fig. 4. This indicates that not all primary porosity had been infilled prior to final sedimentation, no trace of an early cement

Plate 4.15

Figure 1.

Wackestone intraclast in Microfacies D horizon. The matrix consists of a silty fine grained sandstone of the same grain size and composition as the sheet sandstones. The small gastropod (arrowed) is broken across at the intraclast margin. Nuia (a) is present in the matrix.
Thin section, KDH880, plane polarised light.

Figure 2.

Relatively small skeletal oncolite, consisting almost wholly of Girvanella filaments, encrusting a nucleus of broken gastropod shell.
Thin section, KDH880, plane polarised light.

Figure 3.

Intraclast whose margins are formed by the shell of a small gastropod. The absence of significant amounts of micritic matrix adhering to the outside of the clast suggests that little hardening of the matrix due to cementation had taken place.
Thin section, KDH880, plane polarised light.

Figure 4.

Foraminiferid test protruding from intraclast margin. Above this, at a, a second foraminiferid is infilled with a silty sand matrix, indicating that this void was not occupied by cement at the time of transportation.
Thin section, KDH880, plane polarised light.

Plate 4.15

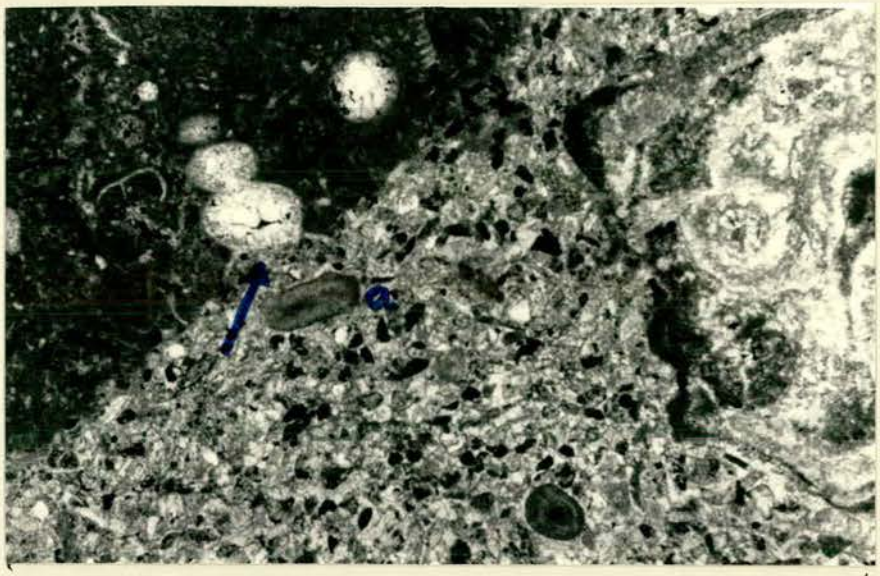


Figure 1
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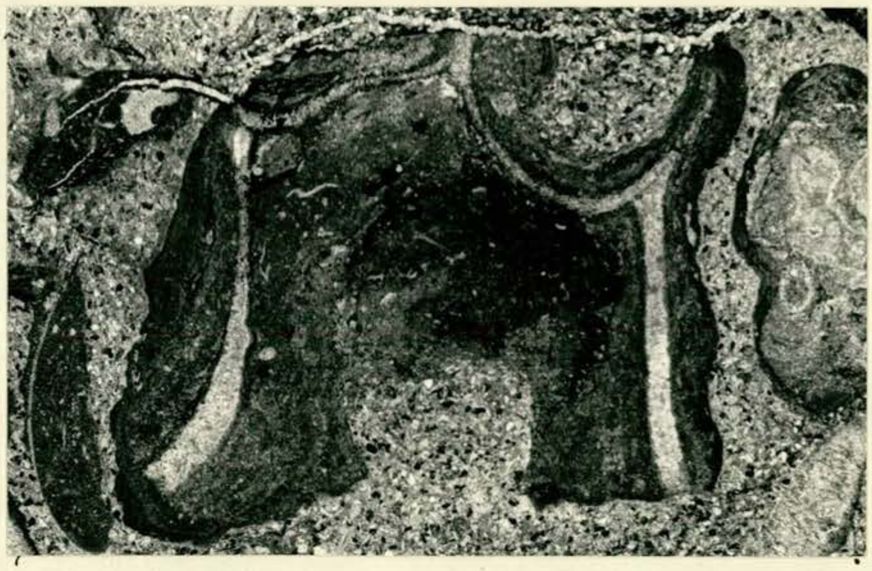


Figure 2
1.5mm

Figure 3 3mm

Figure 4 1mm

generation being seen within such voids. The diagenetic implications of this are discussed in section 4.2.14.

ii) Intraclasts where the grain margins are formed by a fossil fragment and contain a lime-mud infilling of the body cavity, but have little or no adherent micrite on the outside of the grain, Plate 4:15, Fig. 3. Such clasts are thought to have been exhumed from an uncemented horizon, the matrix having no inherent strength.

4.2.15(i) Interpretation of microfacies D

The presence within the intraclastic unit of a matrix closely similar in composition to the silty fine sands that constitute a distinctive non-carbonate facies in the member, is thought to indicate a related mode of formation. As outlined in section 4.2.16, the sheet sandstones are thought to have been deposited from storm-generated, sediment-laden currents originating in the littoral or shallow sub-littoral zones. A major difference, however, must be in the markedly greater erosive capability of the current that produced the intraclastic horizon.

The Holocene carbonate sediments of the Persian Gulf described by Shinn (1969) undergo lithification at or near the sediment surface, forming continuous layers up to 15cm thick. Similar phenomena are described by Taylor and Illing (1969) from Holocene intertidal and sub-tidal sediments of Qatar, where early lithification results in the formation of lumps that eventually coalesce to form irregular sheets. As outlined in section 4.2.14 a similar process is thought to have produced microfacies A, B and C. Microfacies D is interpreted as a storm deposit, formed by the exhumation from a variably lithified substrate, of carbonate lumps or nodules, during an exceptional storm event although, unfortunately, no primary sedimentary structures that might confirm this interpretation were seen. A similar mode of formation has been proposed for many other ancient intraclastic conglomerates of varying ages (Kelling and Mullin 1975, Harms et al., 1975, Jones and Dixon, 1976, Kazmierczak and Goldring, 1978, Sepowski, 1978, Kreisa, 1980) and comparable modern sediments (Kumar and Sanders, 1976). The silty fine sand matrix was most probably deposited from suspension, and infiltrated into the interstices of the carbonate gravel deposit.

4.2.16 Sheet sandstones

Chloritic, silty fine sands interbedded with the limestones forma distinctive feature of the Stinchar Valley Member, being restricted in occurrence to this stratigraphic unit. Varying in thickness from 3 to 50cm these planar bedded sandstone bodies have sharp, sometimes erosive bases, Plate 4:16, Fig. 1, and diffuse bioturbated tops, Plate 4:16, Fig. 2. Bioturbation at the base of a sandstone unit is rare, and occurs only below the thinner units. Bioclastic material, usually oncolites, occur in the lower part of a bed, Plate 4:16, Fig. 3, although in general the sandstones are unfossiliferous. One exception to this is the lowest of the three sandstones seen in the disused quarry near Minuntion (NX29 2208 9112). This 8cm thick bed, occurring 3.5metres above the base of the Limestone Formation, contains relatively abundant brachial valves of Valcourea confinis, whose parallel alignment picks out a faint horizontal lamination in the sandstone. Grading of the sand is not seen, nor is any internal rippling. Following the conclusions of Goldring and Bridges (1973) these sandstones are interpreted as representing single depositional events. Evidence for this interpretation is provided by the restriction, in most cases, of the otherwise ubiquitous burrowing to the top few centimetres of a sandstone bed, animal escape structures are not seen. Similar sandstone beds have been described and similarly interpreted, from ancient deposits, by Goldring and Bridges (1973), Brenchley et al. (1979), Kreisa (1981), and from Holocene deposits by Kumar and Sanders (1976). In all these cases these sediments occur or are inferred to occur in inner shelf or lower shoreface situations, and are interpreted as having been deposited from storm generated currents. The mode of transportation is, however, poorly understood (Kumar and Sanders, 1976); both turbidity currents (Hayes, 1967), and more diffuse gravity flows (Swift, 1976) having been adduced as possible mechanisms. The source of the sediment seen in sheet sandstones is generally regarded to be either the beach or nearshore zones (Reineck and Singh, 1972, Smith and Hopkins, 1972, Swift, 1976).

Plate 4.16

Figure 1.
Cut surface showing the sharp, slightly erosive bed of a sheet sandstone.
Specimen no. CB/8/79.

Figure 2.
Top of sheet sandstone, bioturbated, with an admixed zone only centimetres thick, most burrow traces are horizontally orientated.
Cut surface 62.37m, Benan Burn Borehole.

Figure 3.
Section through sheet sandstone, showing oncolites (arrowed) and other biogenic carbonate fragments concentrated at the unit base.
Specimen no. CB/7/80.

Plate 4.16

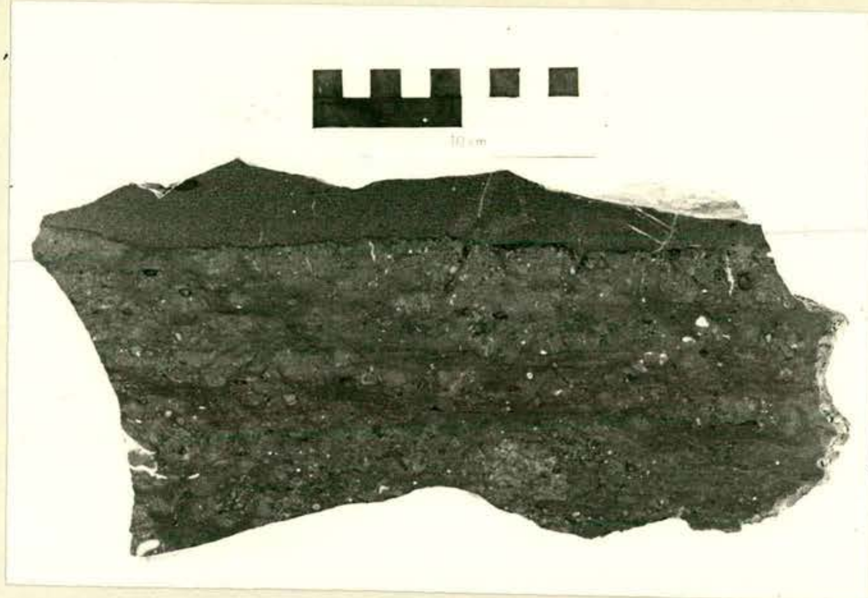


Figure 1

Figure 2

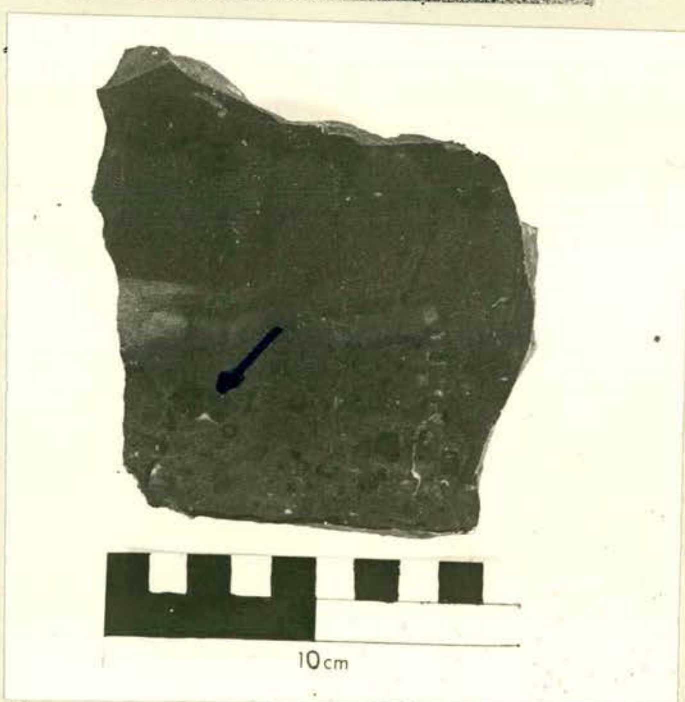


Figure 3

(2) Post-mortem breakdown of calcareous algae

Neumann and Land (1969) concluded that breakdown of the green algae Halimeda, Penicillus, Rhizocephalus in the Bight of Abaco, Little Bahamas Bank, provides more than sufficient material to account for the sediment actually deposited in that area, and may also contribute sediment to adjacent deep sea areas. Steiglitz (1972), and Stockman et al. (1967) reached a similar conclusion having analysed sediments from Bimini lagoon, Bahamas and South Florida, respectively. In each case the lightly calcified chlorophyte Penicillus is the major contributor.

Whilst it is not possible to recognise any such algal material in the Stinchar Limestone Formation it is worth noting that fine sponge spicules are abundant, and may have been a significant source of carbonate.

(3) Breakdown of non-algal, skeletal grains

Algae and fungi may also provide fine-grained carbonate by breakdown of skeletal substrates as a result of infestation of these agents (Perkins and Halsey, 1971). Klement and Toomey (1967) propose that the ancient cyanophyte Girvanella fulfilled this function in Lower Ordovician limestones of west Texas. Whilst infestation of carbonate substrates by non-calcareous cyanophytes is well documented (Ginsburg, 1964, Bathurst, 1966, Kobluk and Risk, 1977) the evidence put forward by Klement and Toomey (1967) attributing a similar role to Girvanella is not felt to be convincing and is equally explicable by fungal rather than algal activity.

In the present day lagoonal sediments of Fanning Island (Pacific) distinctive, fine grained, carbonate particles produced by the boring activity of the siliceous sponge Cliona constitute 30% of all carbonate sediment (Futterer, 1974).

Within the Stinchar Limestone Formation there is little evidence to suggest that the latter mechanisms may have been significant, for whilst micrite envelopes and grain margin infestations are present they are not particularly abundant. For this reason it is felt likely that the first two mechanisms were operative. Palaeomagnetic studies have indicated that during the Middle Ordovician the rocks now forming the Barr Group occupied a tropical to sub-tropical position on or southeastwards of the equator (Briden

In the Stinchar Limestone Formation there are no obvious sandstone bodies, either beach or shoal, from which the type of material seen in the sheet sandstones could have been derived. The distribution of the sands, they occur only in the Stinchar Valley Member, suggests that the sediment source would most probably have existed between the areas in which the Stinchar Valley Member and other parts of the Formation, now found to the north, were deposited. In such a situation the source must have been offshore. Two possibilities are discussed in section 4.4. , one an offshore shoal or small island, the other a probable tidal or distributary channel.

4.2.17 Origin of lime mud

Within the Stinchar Limestone Formation as a whole, lime mud, now patchily neomorphosed to microspar, is thought to be the main form in which calcium carbonate was deposited. Due to neomorphism it is not possible to determine the origin of the sediment by direct observation. For this reason it is desirable to discuss the processes by which present day lime muds form and comment on the applicability of these to the Stinchar Limestone Formation carbonates. Present day lime muds may be produced by the following processes:

(1) Direct precipitation from seawater

In shallow (1-3m) hypersaline areas on the leewards side of Andros Island, Great Bahamas Bank, aragonitic muds (Drewites) are being actively deposited. Rapid deposition of $CaCO^3$ is indicated by loss of calcium, pCO^2 and alkalinity (Cloud, 1962). Cloud also demonstrated that production of lime mud by codiacean green algae can only account for atmost 25% of the total sediment deposited, and that carbonate precipitation occurs mostly during the Summer months. Oxygen and carbon isotope analyses presented by Lowenstamm and Epstein (1957) were interpreted as indicating an algal origin for the muds but are also consistent with inorganic precipitation at temperatures recorded at this time of year (Milliman, 1974). Precipitation of carbonate has been thought by many authors (Lalou, 1957, Oppenheimer, 1960, Greenfield, 1963, Carroll et al., 1965) to be strongly influenced by the activity of denitrifying bacteria living within the sediment. Cloud (1962) and other workers, have questioned this conclusion as bacteria have not been observed to alter pore water chemistries.

et al., 1976, Scotese et al., 1979). Frakes (1979) suggests that Ordovician reefs, of which the Craighead Limestone (Appendix IV) is one, developed only within 30^{0} of the equator. The presence of dasycladacean algae, present day forms of which are limited to low latitudes (Wray, 1976) is evidence supporting the palaeomagnetic results. At tropical to sub-tropical latitudes the temperatures thought necessary to facilitate the inorganic precipitation of calcium carbonate (Milliman, 1974) would almost certainly have been attained for at least part of the year. It is not possible to assess the extent to which post-mortem breakdown of calcareous algae acted as a source of fine grained carbonate, although given the probable warm climatic conditions this may well have been significant.

4.2.18 Limestone/Shale rhythms

The alternation of calcareous and non-calcareous horizons in the Stinchar Limestone Formation is important in the genesis of nodular limestones as outlined in section 4.2.11.

The non-calcareous component of the rhythm, is a moderately well cemented silty clay, of primary, sedimentary, rather than secondary, diagenetic, origin. Evidence for a primary origin is provided by:

i) The presence of burrow traces within the clay rich horizon.
ii) Skeletal grains are present, had the clay rich horizon formed as a result of pressure-solution processes, no small carbonate grains would remain.
iii) The clay rich horizons do not pass laterally into stylolites, as is the case with the clay seams formed by pressure solution processes, described by Wanless (1979).

There are various mechanisms by which a primary alternation of carbonate and rich horizons may originate.

In the most recent paper on limestone/shale rhythms, Evans et al. (1977) conclude that variations in the supply of clastic sediment acted as the primary controlling factor. In a concise argument these authors discount previous hypotheses invoking diagenetic (Hallam, 1964) and eustatic sea level change (Bruckner,

1953) controls. Tectonic control is important in that tectonism is related to overall patterns of sedimentation. Three mechanisms are thought by Evans et al. to be important in controlling sediment supply.

(1) Major storm activity, periodically redistributing sediment. Within the Stinchar Limestone Formation the products of storm activity are readily recognised, see section 4.2.14, 4.2.15, and this factor is not thought to have been important. It is possible, however, that sporadic, low frequency, rainfall, such as is seen in arid regions, might cause a sudden influx of sediment, as a result of flash floods.

(2) Point source migration through time, e.g. the migration or blockage of river or stream mouths, such as happens during major storms (High, 1969).

(3) Turbidity currents, periodically swamping the background pelagic sedimentation in deep sea regions.

Another alternative is that frequent volcanic eruptions in the arc terrain that various authors consider to have lain to the north of the Girvan area provided the fine grained material. X.R.D. analysis of the clay fraction 4 indicates the presence only of chlorite and illite and mixed layer clays. The montmorillonite typical of bentonites, and therefore indicative of contemporaneous volcanic activity is not seen. This observation is of limited worth as burial of these horizons under the full thickness of Ordovician succession seen in the Girvan region would be more than sufficient to produce the submetamorphic temperatures at which Millot (1970) and Powers (1967) consider montmorillonite alters to illite and/or chlorite. Eruptive activity in an arc terrain is considered an unlikely source of material for the Limestone Formation clay interbeds, as evidence for the erosion of such a terrain is not seen until the Caradoc (Kelling, 1962).

4.2.19 Diagenesis of the Stinchar Valley Member

Certain aspects of the diagenetic evolution of the Stinchar Valley Member have already been discussed in sections 4.2.6-4.2.14, concentrating on the nature of the features produced by early diagenesis. In this section the type of processes thought to be involved in cement precipitation and modification of primary fabrics will be discussed.

The most important cement type present in this, and most other parts of the Formation, is thought to have been micrite, precipitated in small scale voids within the lime muds, but now seen as neomorphic microspar. Spar filled primary voids occur within the body cavities of gastropods, foraminiferids, ostracods, articulated brachiopods and shelter cavities beneath the larger and more complex skeletal remains of gastropods and trilobites. Two carbonate cement types are present:

(a) Cloudy, inclusion-rich, faintly fibrous, botryoidal growths, Plate 4:17, Fig. 1, similar to those cements interpreted elsewhere in this thesis as representing the remains of fibrous, marine cements.

(b) Clear, near equant fine spar, never seen to occur as an earlier cement generation that (a).

Pyrite may occur as a void filling cement within primary voids as framboids, Plate 4:17, Fig. 2, and aggregates of small euhedral crystals possibly infilling burrow systems and may possibly replace carbonate in Girvanella filaments, Plate 4:17, Fig. 3. Voids initially infilled with fibrous cements do not contain pyrite as a later cement generation and vice versa. Clear equant spar may infill the whole of a given void, but if either fibrous, inclusion rich or pyrite cements are present will only occupy the central areas of the cavity. Internal sediment may occur in any void, but whilst it can be demonstrated to have infiltrated after the growth of the fibrous, inclusion rich cement it never postdates the growth of the clear, sparry cement.

The abundance of pyrite indicates a high initial abundance of organic material, the presence of which provides a primary control over the precipitation of pyrite, the other being the availability of dissolved sulphate (Berner, 1970, 1980). The presence of large amounts of organic material will inevitably result in a far more complex set of diagenetic reactions than would occur in a clean washed carbonate sand (Bathurst, 1976). The breakdown of this organic material by bacteria and fungi will result in sulphate reduction and associated ammonia formation, which together constitute the two major processes whereby Ca^{++} may be precipitated from pore waters (Berner, 1980) the former also controlling pyrite formation.

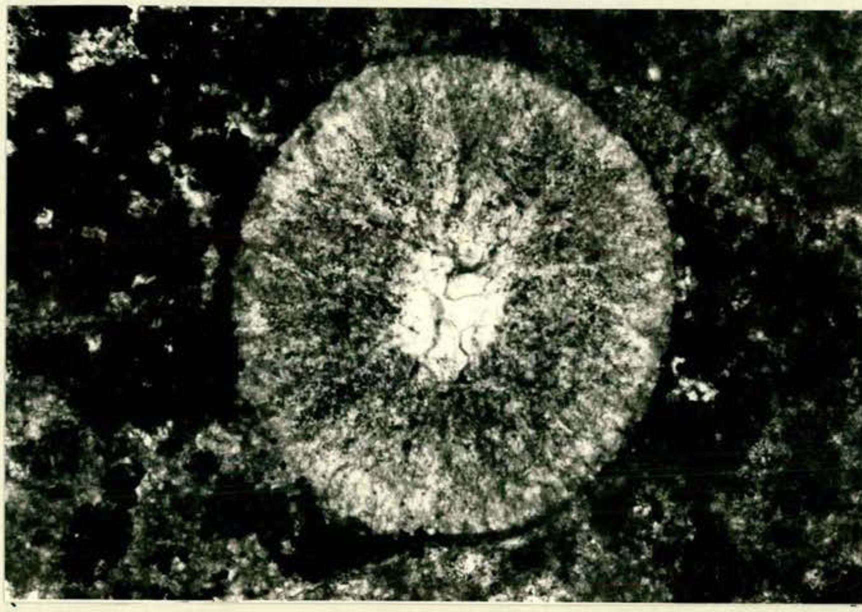
Plate 4.17

Figure 1.
Dark, inclusion rich, faintly fibrous non-ferroan calcite within foraminiferid test. Both cement and shell wall are neomorphosed.
Thin section, MN/1/79A, plane polarised light.

Figure 2.
Disseminated pyrite framboids in patchily neomorphosed algal lime mudstone.
Thin section, 29.59m, Benan Burn Borehole, plane polarised light.

Figure 3.
Pyritized tangle of Girvanella filaments showing cabled growth form.
The pyrite is probably a replacement of calcite, rather than a primary mineralization of the mucilaginous sheath of the alga.
Scanning Electron Micrograph.
Insoluble residue 20m below top of Stinchar Valley Member, Benan Burn.
Scale bar = 100µm.

Plate 4.17



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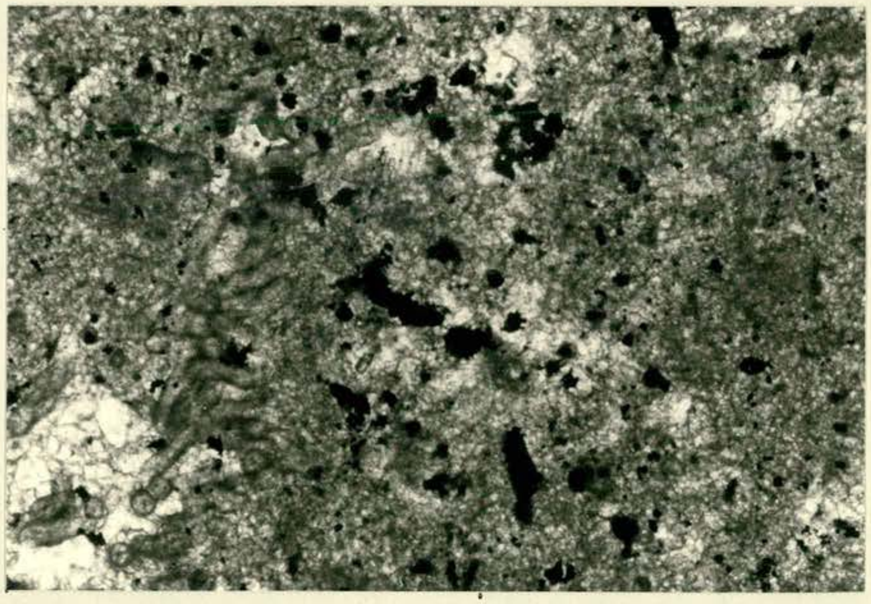

Figure 2
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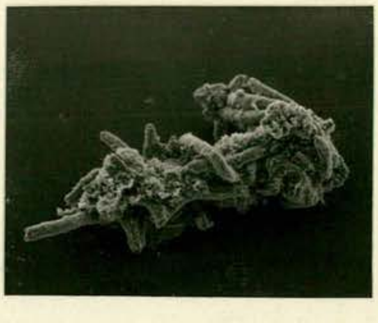

Figure 3

The variety of different void fillings may be a reflection of an uneven distribution of organic material within the sediment, in the following manner:

Precipitation of pyrite precursor minerals within voids and as framboidal aggregates throughout the sediment is thought to occur primarily within the zone of bioturbation (Berner, 1980). The major controlling factor over this process will be the availability of H_2S, produced by sulphate reducing bacteria breaking down organic matter, this will depend on:

i) The initial availability of organic matter.
ii) The extent to which H_2S is lost as a result of bioturbation.

Thus in areas either lacking abundant organic matter, or intensely bioturbated, pyrite is unlikely to form. Continued sedimentation will result in an upward movement of the zone of bioturbation/pyrite precipitation. Below this zone anaerobic conditions prevail and further bacterial activity results in ammonia (NH_4^+) buildup as a result of nitrogen diagenesis and sulphate reduction. High concentrations of ammonia will increase pH (Berner, 1980). This increased alkalinity may bring about the precipitation of calcium carbonate, a process reported by Berner et al. (1978) as occurring below 20cm in present day sediments. Bicarbonate ions necessary for the formation of calcium carbonate may be supplied by the diagenesis of carbon in the same organic matter, again as part of the sulphate reduction process. This may have provided the carbonate for at least some of the equant spar that occurs as a late stage void fill. Carbonate now seen as cement may also have been derived from other sources. Metamorphism of aragonite to calcite, a process discussed later in this section, yields a small amount of $CaCO_3$ (Harris and Matthews, 1967, Pingitore, 1970). Aller (1982) reports dissolution of molluscan debris in highly bioturbated sediments, due to suppression of alkalinity buildup. Increased alkalinity, lower in the sediment, may result in the precipitation of carbonate, as outlined above. Compaction of clays in the silty interbeds and concomitant dewatering may also be a source of carbonate (Powers, 1967, Oldershaw and Scoffin, 1967).

Body cavities containing fibrous cements are not seen to contain pyrite, although they may be finally infilled with internal sediments. It is probable that as a result of the precipitation of this early cement, voids of this type followed a different development from those containing pyrite or equant spar as the first cement generation. Cementation in these cases is thought to have taken place as a result of direct precipitation from seawater. Whilst the processes outlined above are certainly feasible, one major problem still exists with regard to the lithification of lime muds. Holocene lime muds have porosities of between 50 and 80% (Weller, 1959, Bathurst, 1970). The source and supply of such large amounts of cement in the absence of significant compaction, presents an apparently insoluble problem (Bathurst, 1970). Certainly it is difficult to envisage any single mechanism that could supply over half the volume of the limestone. Complete infilling of all available porosity is not, however, necessary for a limestone to acquire considerable mechanical strength. Taylor and Illing (1969) describe hard, lithified, but only partially cemented layers of limestone from the Persian Gulf, these having porosities of up to 40%. Therefore only minor porosity reduction by cement precipitation is necessary before a limestone becomes resistant to compaction, evidence for which is lacking in those parts of the Member interpreted as having lithified near the sediment surface.

Apart from cementation, the major diagenetic process affecting the Stinchar Valley Member carbonates is neomorphism. This term was proposed by Folk (1965) for "all transformations between one mineral and itself or a polymorph". Bathurst (1976) discusses in detail the various types of neomorphic processes that may occur in carbonate diagenesis. Of these the following are thought to have been active during diagenesis of the Stinchar Valley Member.

(a) Transformation of aragonite to calcite without an intermediate void stage (polymorphic transformation). Skeletal grains of former aragonitic mineralogy are now preserved as calcite and have undergone major loss of primary structures, Plate 4:18, Figs. 1 & 2 and captions.

(b) Aggrading neomorphism, the replacement of fine grained carbonate by a coarser-grained sparry mosaic (Bathurst, 1976). The gradation

Plate 4.18

Figure 1.

Heavily neomorphosed gastropod shells showing almost complete loss of original structure.

Thin section, 68.16m, Benan Burn Borehole, plane polarised light.

Figure 2.

Patchy neomorphism of lime mud.

Thin section, 68.07m, Benan Burn Borehole, plane polarised light.

Figure 3.

Detail of neomorphic microspar in wackestone, showing the diffuse boundaries to the sparry area and irregular crystal boundaries.

Thin section, 68.07m, Benan Burn Borehole, plane polarised light.

Plate 4.18

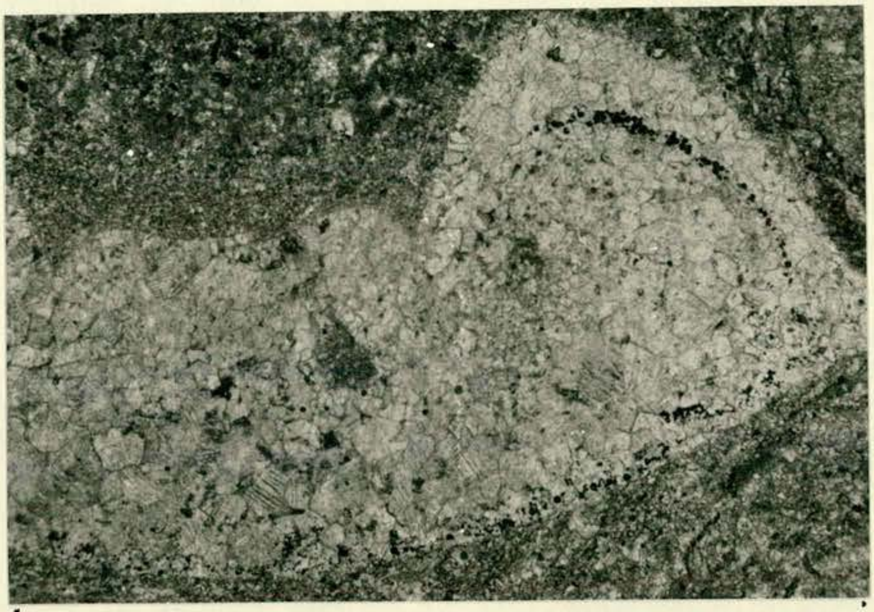

Figure 1
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Figure 2
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Figure 3
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within a thin section from fine grained, micritic, calcite, to coarser microspar, Plate 4:18, Fig. 3, and the general lack of plane crystal boundaries in the microspar, Plate 4:18, Fig. 4, are indicative of this process. Aggrading neomorphism is generally considered to occur relatively early in diagenesis, overlapping in time with cement precipitation (Bathurst, 1976, p.499).

4.2.20 Fossil algae: description and environmental significance

4.2.20(i) Girvanella

Girvanella is the most abundant fossil algal seen in the Stinchar Valley Member. The vast majority of growths are of filaments whose diameters are characteristic of G.problematica, Nicholson and Etheridge, although a wide variety of growth forms, some of which do not conform with the original diagnosis, are seen. The affinities of Girvanella have in the past been the source of much debate, the fossil having formerly been interpreted as a foraminiferid (Nicholson and Etheridge, 1878), sponge (Seely, 1885) and green alga (Rothpletz, 1891, Brown, 1894, Johnson, 1961, 1963). Riding (1977) interprets the calcified sheaths of Plectonema gleophilum, a present day freshwater cyanophyte as an analogue for the similarly filamentous, calcareous Girvanella. This comparison strengthens the arguments of Pia (1918, 1927) and Fremy and Dangeard (1934), resulting in a broad cyanophyte affinity being accepted. Drouet (1968) and Lauritzen and Worsley (1974) suggest that there is a close affinity between Girvanella and the present day cyanophyte family Oscillitoriaceae, although Riding (1975) points out that other extant blue-greens may provide equally valid analogues.

4.2.20(ii) Growth forms present in the Stinchar Valley Member

(1) Bedding-parallel filament bundles, Plate 4:8, Fig. 3, particularly common in microfacies C (hardground) horizons, interpreted as the remains of algal mats. As well as horizontally orientated filaments, tufts of filaments growing vertically and cabling round each other are also present, often seen as part of the same growth, Plate 4:19, Figs. 1 & 2. In general morphology this growth habit closely resembles that of certain present day oscilliatoriacean algae that form subtidal and intertidal mats. Golubic (1973) illustrates two types of tufted mat, reproduced in Fig. 4:3, formed by Scytonema, Oscillatoria and Spirulina. Horodyski (1979) describes

Plate 4.19

Figure 1.
Section through a complexly organised stromatolitic algal mat composed of Girvanella filaments. Basal parts of the mat are composed of parallel aligned filaments, whilst upper parts of the growth are 'tufted', the filaments 'cabling' around each other.
Thin section, 30.33m, Benan Burn Borehole, plane polarised light.

Figure 2.
Detail of part of the same mat as shown above, illustrating the two types of filament organisation described above.
Thin section, 30.33m, Benan Burn Borehole, plane polarised light.

Figure 3.
Cut surface of core, showing small Girvanella oncolites concentrated in a winnow horizon.
71.72m, Benan Burn Borehole.

Figure 4.
Discrete, rounded, grain of tightly intertwined Girvanella filaments, perhaps derived from a stromatolitic algal mat.
Thin section, 71.70m, Benan Burn Borehole, plane polarised light.

Plate 4.19

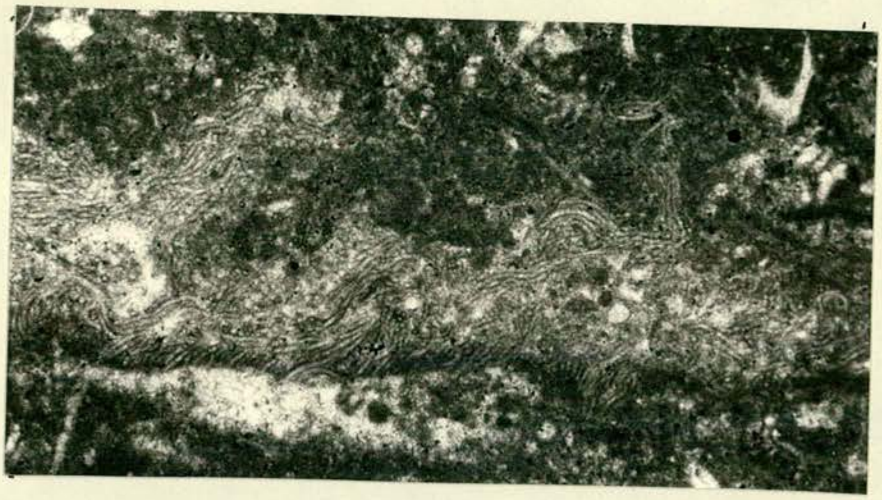

Figure 1
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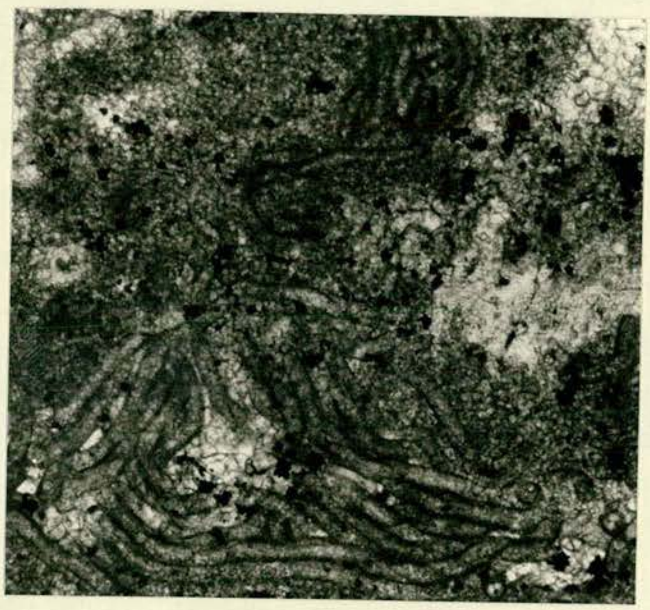

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tufted peritidal algal mats from Laguna Mormona, Baja California, dominated by the Oscillitoriacean Lyngbya aesturii. The tufts in these mats are formed by the clumping together of filaments during exposure of intertidal mats, or by air bubble entrapment in subaqueous mats, see also Golubic (1973) and Fig. 4:3. Horodyski also stresses the importance of motility, a characteristic of oscillitoriacean algae, in the formation of tufts. It is suggested that on the basis of the similarity in structure between the Girvanella mats in Plate 4:19, Figs. 1 & 2, and others, illustrated in Chapter 5, and that of certain present day oscillitoriacean algae mats, an affinity with this particular family might reasonably be proposed for at least the tufted mat growth form of Girvanella.

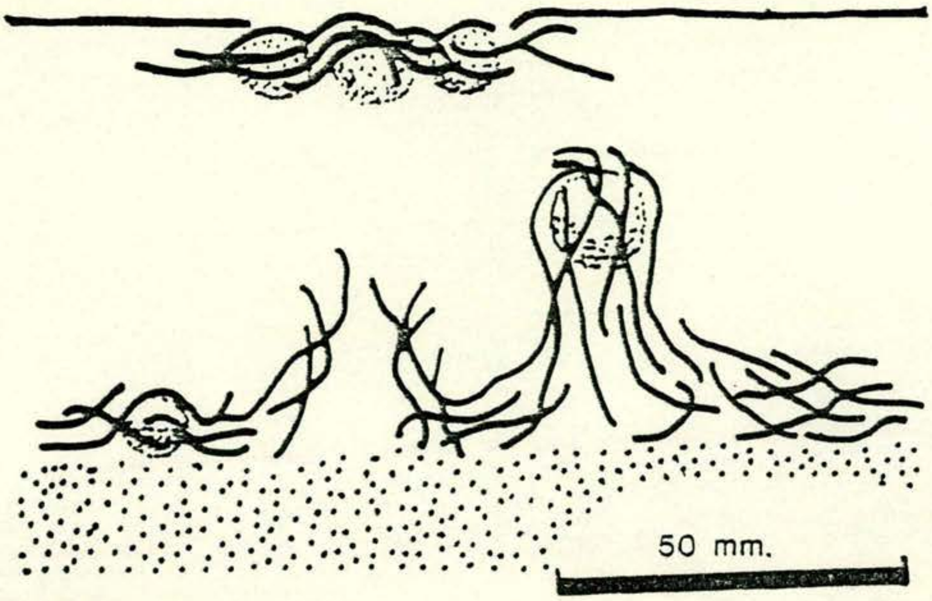
(2) Oncolites: compound oncolitic growths of Girvanella and indeterminate non-filamentous algae are moderately abundant throughout the Stinchar Valley Member. The oncolites vary in size from 5mm to 2-3cm and are also highly variable in terms of their external morphology. Small oncolites,<1cm, are in general nearly circular in cross section and have relatively regular outer margins, Plate 4:19, Fig. 3. Larger oncolites,>1cm, tend to be more irregular in shape, often having complex outermargins, and internal laminae. Skeletal oncolites (Riding, 1977) composed solely of Girvanella filaments are in general rare, although the microfacies C horizon illustrated, Plate 4:6, contains several of these irregular growths.

Oncolite substrates are provided in all cases by either skeletal debris or intraclasts of wackestone identical to that which forms the main bulk of the Member. Alteration of the substrate margins may occur, perhaps as a result of algal, or associated fungal or bacterial activity. The smaller oncolites are most abundant in the lower part of the member, where they often occur in storm-produced shell lags, Plate 4:19, Fig. 3, and also in the packstones transitional between the Stinchar Limestone Formation and the overlying Mudstone Member of the Benan Formation.

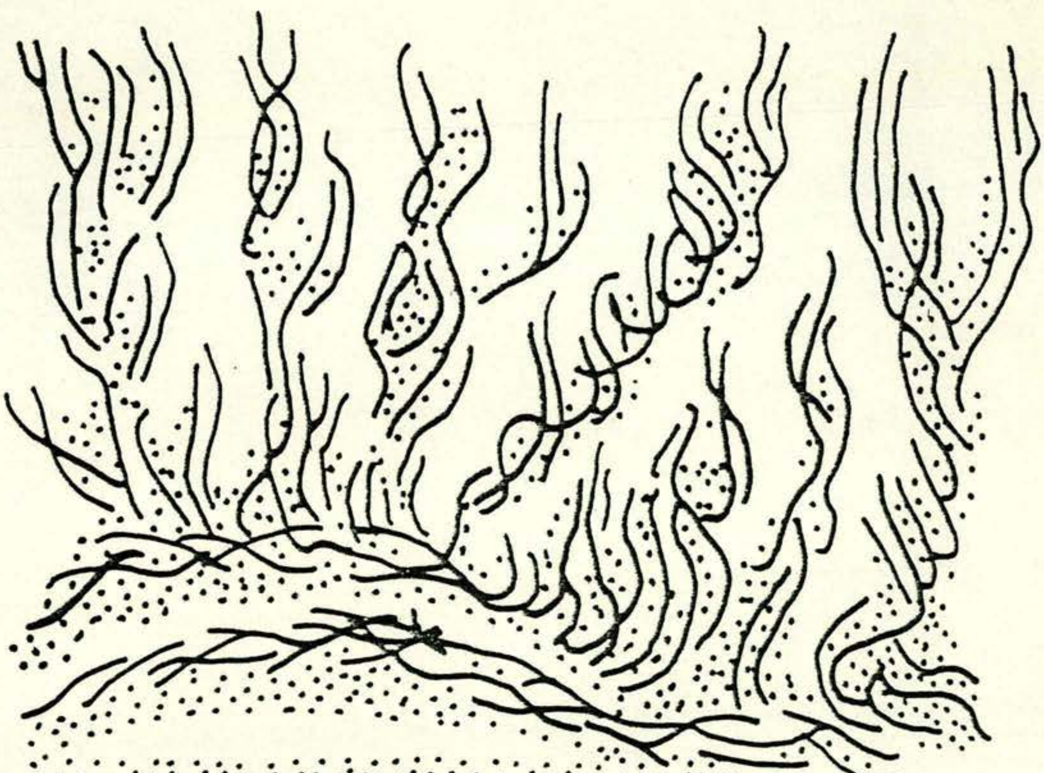
(3) Small, flocculose, loosely entwined bundles of filaments that may have been produced by the lifting off of filaments by gas bubbles formed within the algal mat, in the manner described by Golubic (1973) and Horodyski (1979) from present day environments. Alternatively bioturbation of subtidal algal mats could also produce

Figure 4.3

Growth forms of present day Oscillitoriacean Cyanophyte algae.



Flocculose mat of filamentous cyanophytes,Oscillatoria and Spirulina,
Parts of the mat are lifted by oxygen bubbles.



Scytonema mat composed predominantly of vertical filament bundles
with entrapped sediment ,growing from a coherent base.

grains of this type.

(4) Small algal lumps, of relatively loosely entwined filaments, forming relatively discrete grains with clearly defined, often rounded margins, Plate 4:19, Figs. 4. Filaments may be organised and aligned parallel to each other or may be complexly contorted and intertwined. Grains of this type are interpreted as fragments of algal mat or skeletal stromatolite disrupted, either by biological or mechanical agents.

Further comments on the taxonomic significance of these and other types of Girvanella growth habits and grain types may be found in section 4.5.3.

4.2.20.(iii) Nuia

The problematic micro-organism Nuia siberica Maslov Plate 4:20 and caption, occurs throughout the Stinchar Valley Member, being most abundant in the lower part. This occurrence is of considerable significance as Nuia has not previously been recorded in this country. When Nuia was first described it was assigned to the codiacean green algae but subsequent authors (Toomey and Klement, 1966, Toomey, 1967, Toomey and LeMone, 1977, Wray, 1977) have suggested that there are insufficient diagnostic features to allow proper identification. In terms of stratigraphic range, Nuia would seem to be restricted to topmost Cambrian and Lower and Middle Ordovician strata (Wray, 1977). The 'genus' has been previously reported only from the U.S.S.R. and U.S.A., with a single occurrence reported from Argentina (Gnoliand Serpagli, 1980), and cited as evidence for the "cosmopolitan aspect" of the genus. It is felt that more information on the Middle Ordovician palaeogeography and the palaeobiogeography of better understood taxa, in S. America, is needed before this conclusion can realistically be made.

Whatever the affinities of Nuia, it would seem to be a fairly reliable indicator of a shallow marine environment, only having been reported from rocks of this facies.

4.2.20.(iv) Dasycladacean algae

These occur throughout the Stinchar Valley Member, usually as fragmented rather than whole individuals. A variety of forms are present, referable to the genus Vermiporella, whose major

Plate 4.20

Figure 1.
Transverse section through fragment of Nuia, showing concentric laminae, faintly fibrous, radial structure and dark central area.
Thin section, 71.28m, Benan Burn Borehole, plane polarised light.

Figure 2.
Reconstruction of Nuia, showing relationship of observed structure (in insets) to the proposed overall structure. After Kinzly-Moore (1979).

Figure 3.
Oblique section through Nuia growth, showing the major features as outlined above.
Thin section, 71.28m, plane polarised light.

Plate 4.20

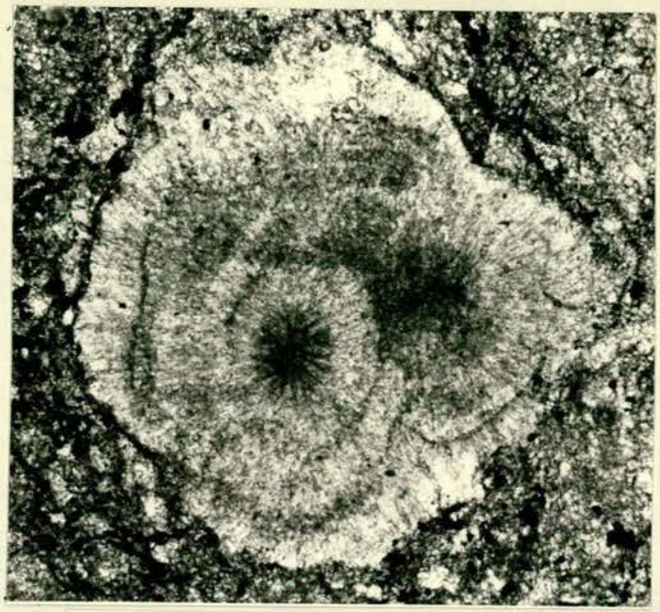


Figure 1

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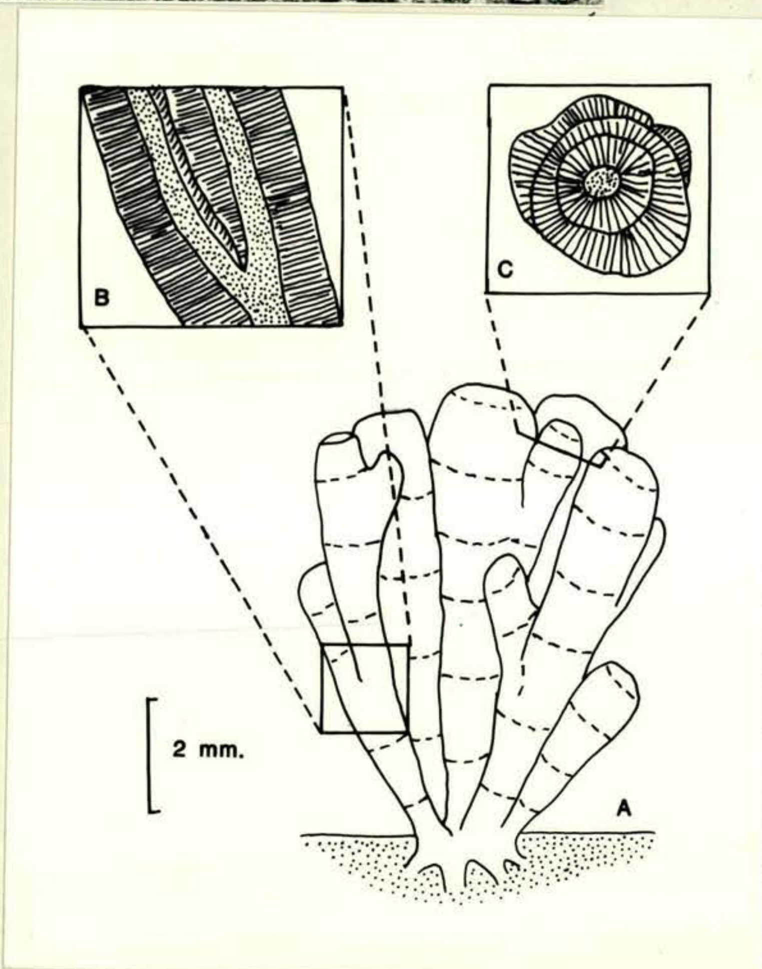

Figure 2

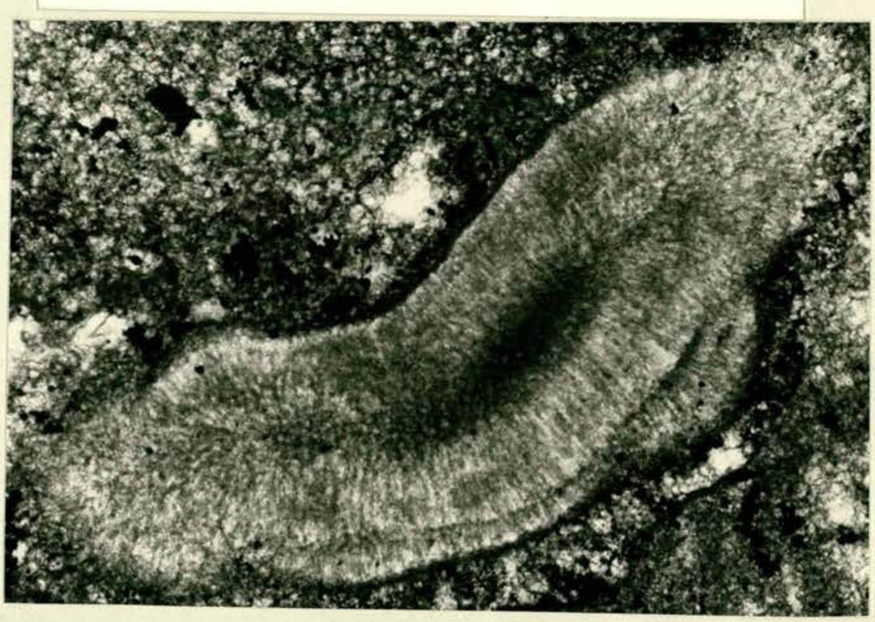

Figure 3

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Plate 4.21

Figures 1 and 2.

Two varieties or 'species' of Vermiporella, different in terms of wall structure.

Thin sections, plane polarised light.

Figure 1, 68.07m, Benan Burn Borehole.

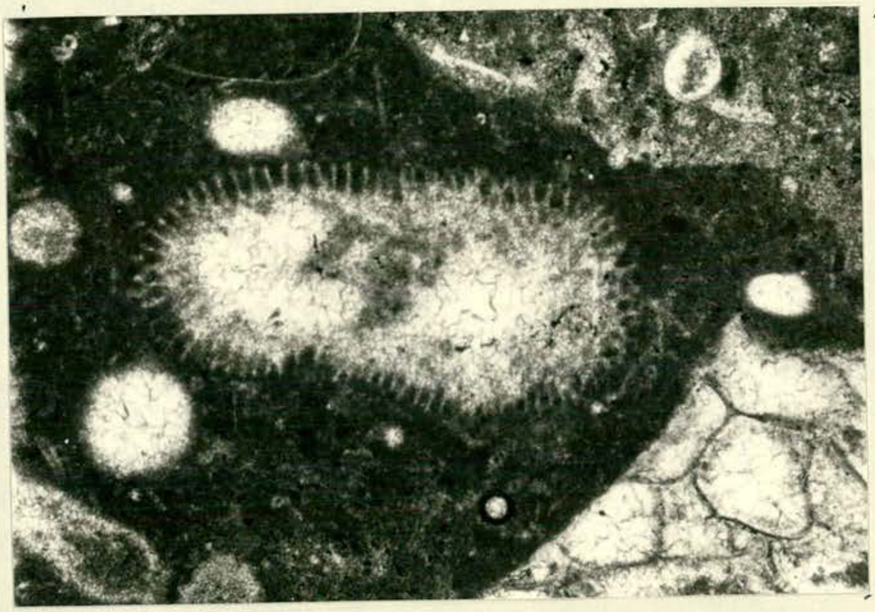
Figure 2, 71.70m, Benan Burn Borehole.

Figure 3.

Fragments of cyclocrinitid algae (arrowed) most probably Mastopora.

Thin section, 68.16m, Benan Burn Borehole, plane polarised light.

Plate 4.21



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features are illustrated in Plate 4:21, Figs. 1 & 2, considered by Johnson (1961) to be the most primitive member of the family. Specific identification of the various forms present has not been made due to the often poor preservation, and the time involved in dealing with a large and often confused literature, for the most part in Russian.

In addition, fragments of cyclocrinitid dasycladacean algae, Plate 4:21, Fig. 3 are also present, usually abraided and often encrusted by Girvanella. No complete individuals were recorded from the Stinchar Valley Member, although abundant at other localities. The form most frequently encountered would appear to belong to the genus Mastopora Eichwald 1840, and described by Nicholson and Etheridge (1880) as Nidulites. Nitecki (1970) places Mastopora in synonomy with Cyclocrinites, and other similarly unsegmented, inflated or globular algae and in 1972 suggested a receptaculitid rather than dasycladacean affinity for the genus. Present day dasyclads occur almost wholly in tropical regions and are most abundant in quiet waters at depths of less than 30m, and commonly less than 5m (Wray, 1977, p.108). Any analogy, in terms of environmental limits and preferences, between modern and ancient algae must, however, be made with caution. In particular, doubt has been cast on the affinities of Vermiporella. Riding and Jansa (1974) and Riding (1977), suggest that a foraminiferid interpretation may be more appropriate, thereby calling the above interpretation into question.

4.2.20.(v) Summary

The calcareous algae within the Stinchar Valley Member include one genus of probable cyanophyte affinity, Girvanella, two possible chlorophyte genera and one problematic micro-organism of possible algal affinity, Nuia.

Girvanella occurs as algal mats, fragments of mats and grains derived from the mats by either physical or biological mechanisms, and also as both skeletal and non-skeletal oncolites. Present day cyanophyte mats are reported as occurring in water depths of up to 18 metres (Ginsburg, 1960) as well as in intertidal areas, although being particularly well developed in shallow, 1-3 metres, water depths (Scoffin, 1970, Neumann et al., 1970, Bathurst, 1974). Information on the conditions under which present day oncolites may develop is scarce, Ginsburg (1960), Gebelein (1969) describe algal biscuits, compared by some authors to ancient oncolites forming in water depths of 2-3 metres. Ignoring the suspect evidence based on the presence of dasycladacean algae, it is never the less obvious that, if the comparisons and conclusions made in the foregoing pages are correct, there can be little doubt that the Stinchar Valley Member was indeed deposited in shallow water at depths probably less than 15-20 metres.

4.2.21 Depositional environment of the Stinchar Valley Member: a summary

Deposition of the limestones assigned to this unit took place as a result of abandonment of the Kirkland Formation fan-delta and submergence of this area which had formerly received mainly clastic sediment. Gradual reduction in clastic sedimentation allowed the establishment of a carbonate-dominated depositional regime. The lime muds that constitute the main sediment type within the member are thought to have been locally produced by inorganic precipitation and/or post-mortem breakdown of calcareous algae. Carbonate deposition was frequently interupted by the influx of fine grained terrigenous sediment, giving rise to an alternation of carbonate and non-carbonate beds. Storm events affecting the area of deposition are manifested by the presence of sheet sandstones and intraclast breccia horizons. Variations in the sedimentation rate and the degree of bioturbation resulted in the deposition of either nodular, non-nodular or hardground microfacies. Hardground horizons formed as the result of prolonged periods of very low, or non-sedimentation. Such horizons underwent early lithification at the sediment surface and are associated with teepee structures formed as a result of the expansion and upwards buckling of the hard layer during lithification. Calcareous algae within the Member indicate shallow water conditions of less than 18 metres, and possibly as little as 2-3 metres and the presence of fenestral fabrics may indicate intertidal conditions at certain horizons. Lateral facies changes within the member are seen at Auchensoul and Minuntion and interpreted as indicating somewhat deeper water conditions.

4.3 Brochloch Member

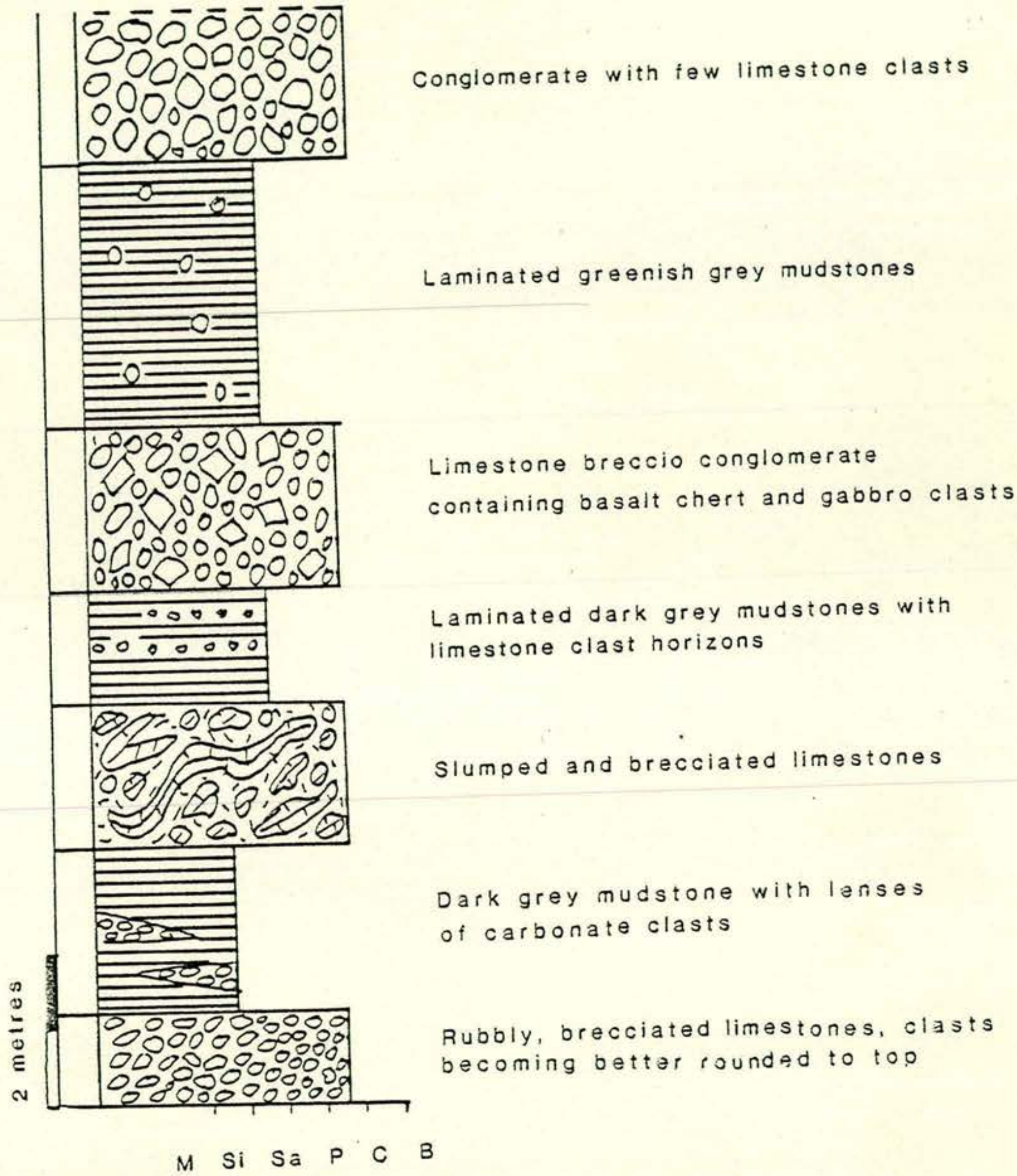
4.3.1 Introduction

Along the Northern flank of the Benan syncline, Stinchar Limestone Formation rocks outcrop in stream beds along the southern side of the Assel valley and in disused quarries around the Craigwells lime kiln, supposedly having been upfaulted as part of the Dupin thrust zone (Williams, 1962). It is at the latter localities that sections assigned to the Brochloch Member are exposed. Whilst a complete section through the Stinchar Limestone Formation is not available at any of these localities the sequence can be assumed to be markedly thinner than in the type localities, Fig. 4:4. The sequences are made up of two main components, redeposited, brecciated and slumped limestones and inter-bedded laminated bluish-grey silts. Henderson (1935) interpreted the limestone horizons as the products of slipping caused by submarine earthquakes, an explanation favoured by Williams.

4.3.2 Section description

Small pebble conglomerates and associated grits, Plate 4:22, Fig. 1, are seen at the entrance to the main quarry to the N.E. of the Craig Wells Kiln (NX29 2560 9505). It is not possible to definitely determine the relationship of these to the main outcrop. The pebbles are dominantly basaltic, well rounded and discoidal, Plate 4:22, Fig. 1, the clast form perhaps indicating abrasion in a marginal marine environment. The main section at this locality is composed of redeposited or slumped limestone horizons up to 2 metres thick with interbedded silts. The carbonate breccias, Plate 4:22, Figs. 2 & 3, consist of both angular and moderately rounded clasts, Plate 4:22, Fig. 3, of algal/foraminiferal wackestones, oolitic packstones/grainstone sand fenestral, oncolitic wackestone. Angular clasts of basalt, red chert, and other lithologies derived from a Ballantrae Complex source area, varying from pebble to cobble sizes, also occur in these laterally discontinuous horizons, Plate 4:22, Fig. 3. In addition to the brecciated units and interbedded with them, slumped carbonates are recognisable by their internal deformation, greater lateral continuity and uniform lithology, Plate 4:23, Fig. 1. Certain slumped horizons are partially brecciated, the clasts being separated by mudstone but

MEASURED SECTION MAIN FACE BROCKLOCH QUARRY



are easily refittable. The interbedded siltstones contain thin fine sand laminae, clasts of limestone and isolated lenses of grainstone and packstone, Plate 4:23, Fig. 2. The top units of the sequence consist of a carbonate clast conglomerate, Plate 4:23, Fig. 3, which passes gradationally upwards into the Conglomerate Member of the Benan Formation. The clasts are moderately well rounded, constitute up to 80-90% of the clasts presented are set in a matrix of coarse lithic sand.

A second section through the Member can be seen in a small quarry 100m (NX29 64 9511) to the N.E. of the main exposure. The sequence is poorly exposed but is similar to that in the main quarry, although no correlation between the two can be made. Extensive tectonism, presumably associated with movement along the Dupin fault complex, is manifested by numerous small scale fault planes, seen in both sections, which may cut out both carbonate and siltstone horizons, and pervasively shear the latter.

200 metres to the S.W. of the main exposure, in the quarry adjacent to the Craigwells lime kiln (NX29 2541 9489) a markedly different carbonate facies is seen. Here, on the E. face of the quarry, flat bedded, non-nodular, algal/foraminiferal wackestones with pockets of ooolitic packstone, form the upper most part of the Stinchar Limestone Formation. The relatively thick siltstone units that characterise the Brochloch Member, as seen in the previous localities, are not present. The contact between the Stinchar Limestone Formation and the overlying Benan Formation conglomerates is strongly erosive, a channel 1-1.5m deep having been cut into the limestones. Whilst carbonate clasts are present in the basal horizons of the Conglomerate Member, their abundance is considerably less than in equivalent levels in the previous sections.

Two further observations on the Brochloch Member are significant:

(a) As noted by Williams (1962) outcrops of serpentinite and basalt occur in close proximity to the Brochloch localities. Whilst movement along the Dupin fault complex may have been considerable (Williams, 1962) the absence of sequences that elsewhere typify the Kirkland Formation is thought to be due to non-

Plate 4.22

Figure 1.

Well sorted small pebble conglomerate at base of Brochloch Member sequence. The clasts are discoidal in form and are segregated into thin horizons (~ 5cm thick) of roughly similar sizes.
Tape measure is 5cm across.
Locality, Brochloch main quarry.

Figure 2.

Rubbly, extremely poorly sorted carbonate breccia horizon in Brochloch Member. The clasts are not angular, this may indicate limited abrasion, perhaps of a partially lithified sediment, prior to final deposition. Horizons of this type may have been emplaced either by rockfall or slumping mechanisms.

Figure 3.

Cut surface of limestone breccio-conglomerate showing presence of clasts of basalt (arrowed).
Specimen no. BS/1/80.
Locality, Brochloch small quarry.

Plate 4.22

Figure 1

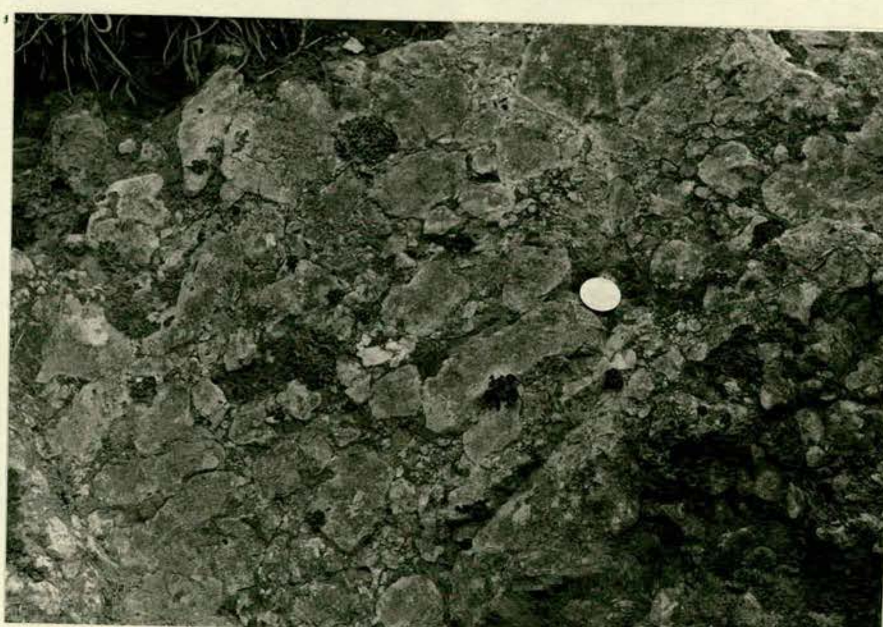


Figure 2

Figure 3

Plate 4.23

Figure 1.

Laterally thinning carbonate breccio-conglomerate unit. The relatively persistant but buckled limestone horizon may have been slumped. Above this horizon note the piling up of pebbles behind a large cobble.

Pen measures, 14cm in length.

Locality, Brochloch small quarry.

Figure 2.

Packstone lens in thick shale horizon, cut across by numerous small faults.

Hammer measures 30cm in length.

Locality, Brochloch main quarry.

Figure 3.

Topmost horizons of the Brochloch Member sequence, showing passage from rubbly limestone, in lower part, to a more conglomerate lithology with an increasing abundance of basaltic and chert clasts.

Tape measure is 5cm across.

Locality, Brochloch main quarry.

Plate 4.23

Figure 1

Figure 2

Figure 3

deposition of these units rather than post depositional faulting.

(b) Amongst the various carbonate lithologies that occur as clasts within the limestone breccia horizons of the Brochloch Member, fenestral, oncolitic/peloidal wackestones, Plate 4:24, Fig. 1, are of particular importance. In these clasts a primary fenestral fabric is cut across by non-fabric selective dissolution voids, Plate 4.24, Fig. 2, that produce secondary fenestrae, occupied by a clear, equant cement, Plate 4:24, Fig. 3. Secondary porosity of this type, and perhaps also the equant calcite cement, most probably developed as a result of diagenesis in either the freshwater, vadose or phreatic environments. Such clasts are thought to provide conclusive evidence for the emergence and early, freshwater, diagenesis, perhaps in a peritidal setting, of at least certain parts of the Stinchar Limestone Formation. It is not, however, possible to determine the location of the sediment from which these clasts were derived.

4.3.3 Depositional environment of the Brochloch Member

Due to the isolated and somewhat fragmentary nature of the Brochloch sections, it is felt that any environmental interpretation must be made with caution. Two possible environmental settings, outlined below and in Fig. 4:5, are felt to be worthy of consideration, and sufficiently certain to warrant the inclusion of the localities within a formal stratigraphic scheme.

(a) The presence of slump units and associated carbonate breccias indicate the presence of submarine slopes that occasionally became unstable. The ground between the main Brochloch and the Craigwells limekiln, exposures, the area across which the facies change outlined in section 4.3.2 takes place, is the most likely location of this palaeoslope.

(b) Normal, or background, sedimentation in the Brochloch Member consisted of silt and fine sand deposition.

(c) Local production of carbonate sediment was minimal, increased water depth is felt to be the most likely cause for this sudden lateral change in the pattern of sedimentation.

(d) The presence of basalt and chert clasts within the carbonate breccia horizons is thought to suggest either:

Plate 4.24

Figure 1.

Clear, non-ferroan calcite spar occupying dissolution voids in oncolitic, fenestral wackestone. The occurence of such a lithology as a clast within the Brochloch Member breccio-conglomerates, indicates subaerial emergence and diagenesis of part of the Stinchar Limestone Formation. Thin section, BSQ/2/81, plane polarised light.

Figure 2.

Detail of the above photomicrograph showing dissolution of peloidal lime mudstone that surrounds the test of a foraminiferial, either Saccaminapsis or Thuraminoides. Dissolution has also affected part of the test well, only a thin micritic line now being seen.

Figure 3.

Near equant, clear, calcite cements in dissolution voids. Thin section, BSQ/2/81, plane polarised light.

Plate 4.24

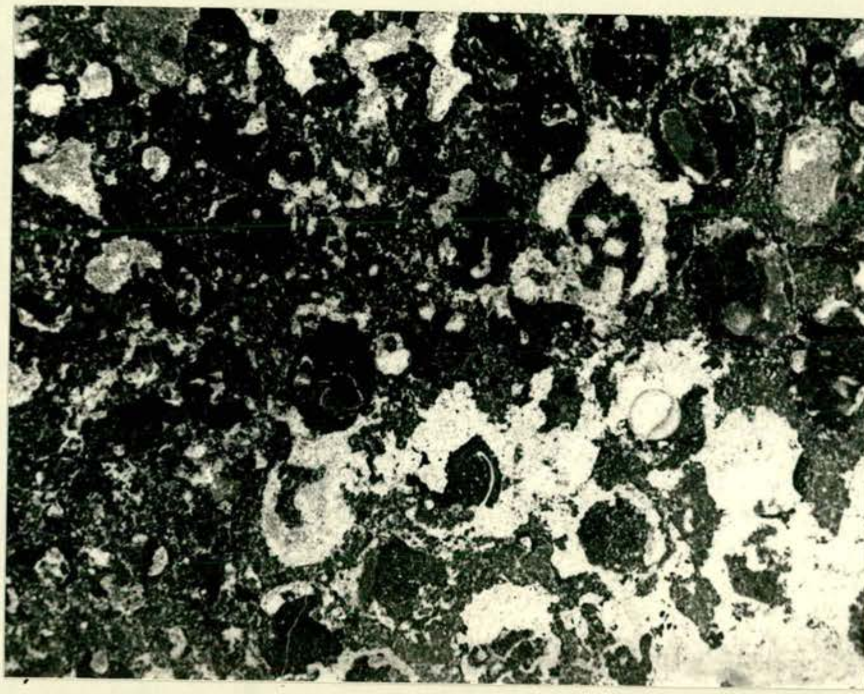


Figure 1

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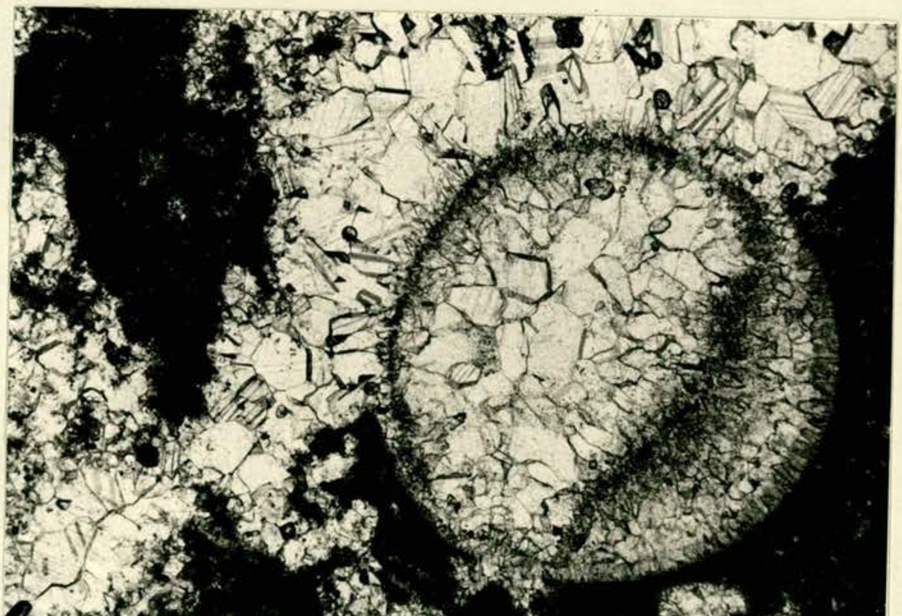

Figure 2

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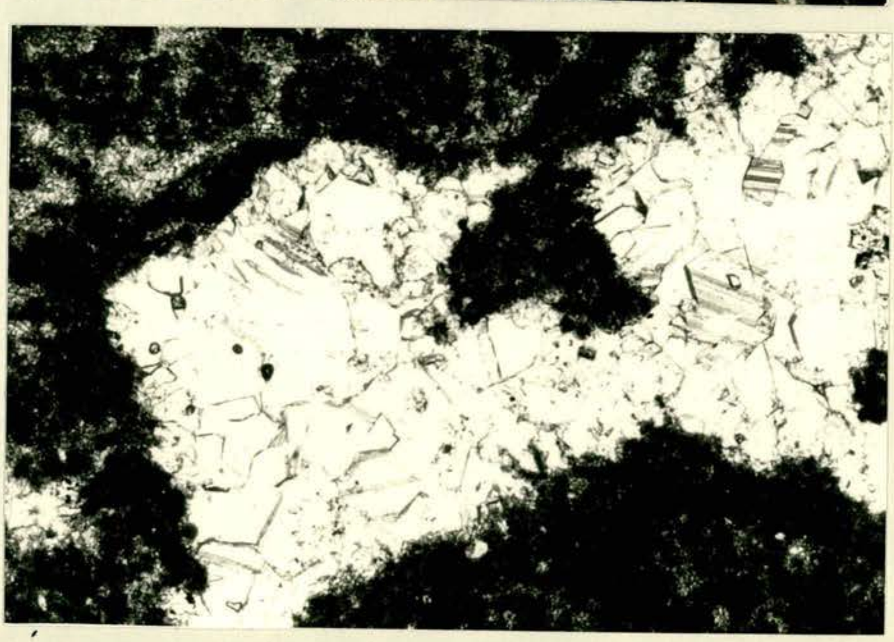


Figure 3

0.5mm

(i) The presence of Ballantrae complex lavas and associated sediments exposed in the wall of the inferred submarine slope and being eroded, or spalling off during earth tremors.

(ii) Sporadic influx of coarse grained sediment from outside the immediate vicinity, although the generally angular nature of these clasts must indicate a lack of abrasion in either fluvial or beach environments.

Depositional Environment 1

This represents deep channel incised into the local Ballantrae Complex basement, Fig. 4:5. The location of this channel may have been the result of the submergence of an incised topography. Clastic, non-carbonate sediment derived from one of the sources outlined above. Carbonate breccias and slump units derived by either:

Undercutting the channel margins, by either tidal?, sediment discharge or bioerosion mechanisms.

Oversteepening of channel margins and subsequent slope failure.

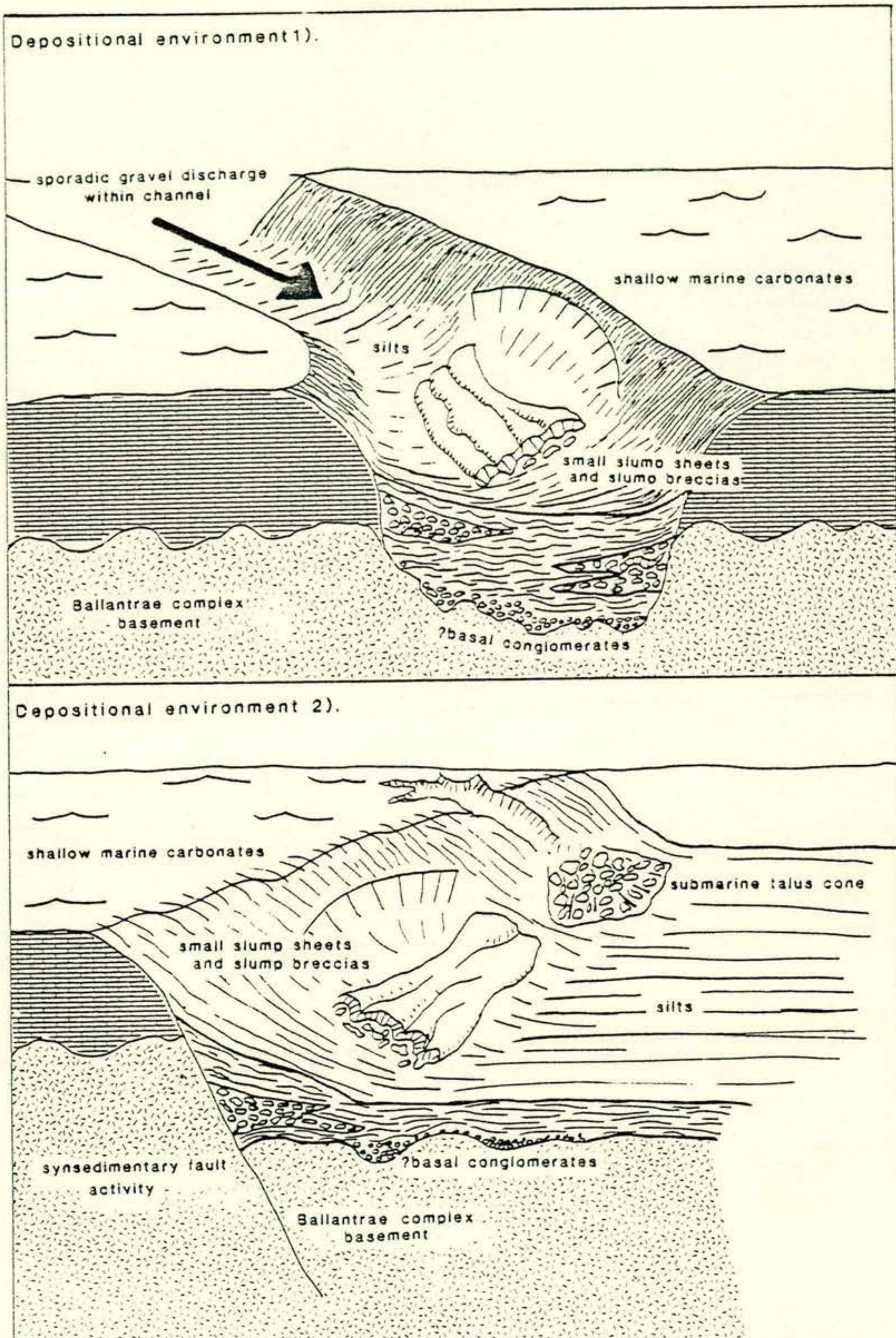
Slope failure as a result of earthquake shock.

A broadly similar facies assemblage has been described from tidal channels that cut into Upper Ordovician shelf sediments of the Oslo region, Norway, by Brenchley and Newall (1979). In this example the marginal areas of the channels are occupied by limestone breccias, whilst central areas contain conglomerates and sands in more proximal reaches and muds in open shelf areas. Intra-formational breccias are also important components of present day channel fill sequences in the Florida Keys (Jindrich, 1969) and Shark Bay, W. Australia (Hagan and Logan, 1975, Woods and Brown, 1975).

Depositional Environment 2

An alternative interpretation of the Member is a base of slope accumulation at a steep margin to a shallow water shelf area, Fig. 4:5. The slope itself may have been produced by either earlier, pre-submergence topography or penecontemporaneous faulting, producing a submarine scarp face. Limestone breccias are of common occurrence in both ancient and modern carbonate slope deposits (Wilson, 1975, Cook and Enos, 1977, and references therein).

Alternative depositional models for the Brochloch Member



Bank or platform margins of the type proposed have been termed by-pass margins (James, 1978), the slope itself being abrupt and too steep for sediment to accumulate on it. By-pass margins are particularly common along block faulted oceanic or platform margins. In present day carbonate environments such deposits frequently occur at reef margins such as Belize (Ginsburg and James, 1973) and Jamaica (Goreau and Land, 1974). The apparent lack of fine grained carbonate in the sequence may be the result of sediment stabilization by algae, as noted by Scoffin (1970), in the shelf areas. Slump units and breccia horizons may have resulted from intermittent movements along faults controlling the platform margins or as a result of oversteepening of the upper slope areas by carbonate accumulation.

4.4 Non-assigned localities south of the Water of Assel: Dupin to Shalloch Hill

4.4.1 Introduction

Along strike from the Brochloch/Craigwells localities further exposures of Stinchar Limestone Formation sediments are seen in stream sections around Dupin farm (NX29 2392 9418) and in small excavations on Shalloch Hill (NX29 2205 9340). Williams (1962) whilst recognizing that variations in facies occurred along strike from Craigwells to Dupin, considered that the sequences exposed were essentially similar. As demonstrated in section 4:3 the Brochloch sequences indicate a particular type of depositional environment which differs from that of the Stinchar Valley Member and also,as will be seen, from the Dupin localities. It is felt that a combined discussion of both Brochloch and Dupin localities would serve only to mask, rather than elucidate, the facies variations present.

4.4.2 Field Observations

Dupin Glen

In the bed of the stream flowing through Dupin Glen (NX29 2365 9410) the sequence summarised by Williams can be recorded. The gravels that occur as the lowest unit in the exposed sequence are granule, pebble and cobble conglomerates, containing moderately well rounded clasts, basalt and chert clasts predominate. Clasts of Stinchar Limestone

Formation lithologies are not seen. Where recognisable bedded horizons occur within the conglomerates they may be clast supported, but matrix supported fabrics are more generally developed. The upper parts of the conglomerate sequence contain 5-10cm thick faintly graded sandstone beds. It is uncertain from the account of this sequence given by Williams (1962) whether he assigns these conglomerates to the Benan Formation or considers them to be 'of confinis age'. There is no break in the sequence between the conglomerates and the overlying purple and green sandstones with pebble bands reported by Williams to contain Valcourea confinis and other brachiopods. The sandstone sequence is about 20-25m thick and fines upwards, becoming more calcareous and fossiliferous in the same manner as the Benan Burn Sandstone Member. The transition into the overlying limestones is obscured by a faulted zone that occurs near the waterfall in the more westerly fork of the burn. Above the fault the local development of the Stinchar Limestone Formation outcrops in a deep, narrow, steep sided gully which is for the most part inaccessible. As far as could be determined, the 20-25m thick sequence consists of planar and thinly-bedded wackestones, silty in the lower parts and becoming purer upwards. It was possible to examine the limestones more closely at a horizon about 17m above the base of the unit. Here the lithology is essentially the same as the main bulk of the Formation, algal/foraminiferal wackestones. Numerous beds at this level contain abundant cyclocrinitid green algae. These are globose forms, up to 4-5cm in diameter with relatively thin walls, Plate 4:25, Fig. 1, and occur to the almost total exclusion of any other large fossil fragments. The extreme abundance of this type of alga is not seen anywhere else in the Formation. Above the gully a break in outcrop of 15-20m obscures the relationship between the limestones and the Benan Formation conglomerates that are the next observed unit in the sequence. Williams (1962) considers this gap to be occupied by his 'superstes' mudstones, presumably on the assumption that, unless removed by erosion at the base of the overlying conglomerates the mudstones are present, and were deposited, across the whole area. Excavations in the stream bed failed to reveal the presence of any mudstones.

Plate 4.25

Figure 1.

Cyclocrinitid algae probably <u>Mastopora</u> sp. in wackestone.
Thin section, DG/6/81, plane polarised light.

Figure 2.

Argillaceous rubbly limestone exposed in Dupin, Mid Burn (NX29,242 942).
Pen (arrowed) = 13cm.

Figure 3.

Detail showing poorly sorted nature of argillaceous rubbly limestone.
Clasts are poorly rounded and consist of oolitic grainstones and packstones as well as oncolitic wackestones.
Dupin.

Plate 4.25

Figure 1

5mm

Figure 2

Figure 3

The sequence as a whole is similar to those seen in the Stinchar Valley Member, and apart from the differences in unit thickness, and the absence of sheet sandstones, represents no great departure from the type section in terms of depositional environment. The absence of sheet sandstones is, however, of considerable palaeogeographic significance as outlined in section 4.2.15.

Dupin Mid-Burn

A highly disturbed sequence through the Member can be seen in and around Dupin Mid-Burn (NX29 2415 9420), 200m E. of Dupin farm. The limestone is variably sheared throughout the section and the sequence may, in part, be repeated by faulting. The succession is more or less as reported by Williams (1962).

Dupin (2) Burn

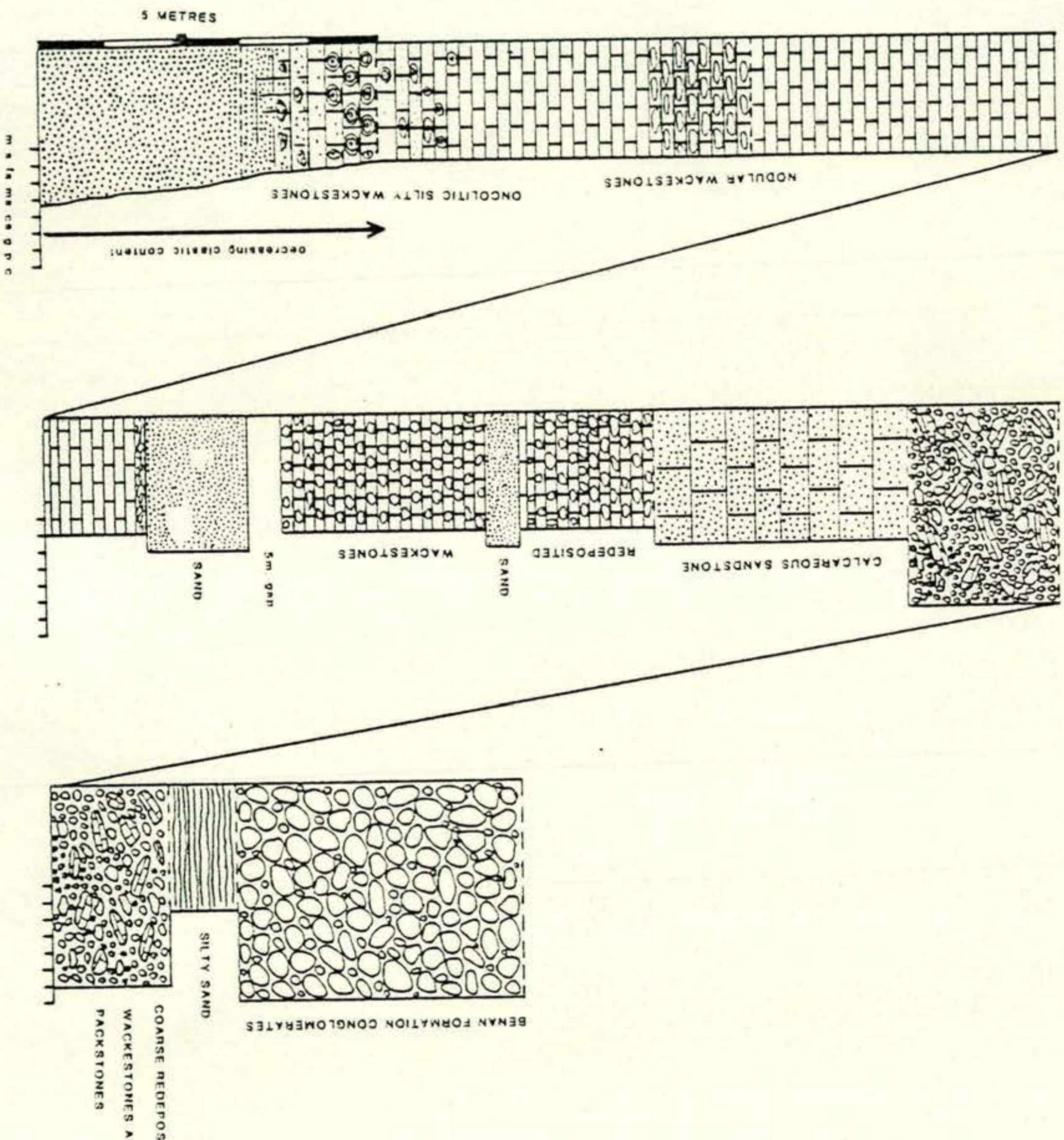
A fuller and less disturbed section through the Member is seen in a second stream 600m E. of Dupin farm (NX29 2445 9425) and summarised in Fig. 4:6. Again a thickening of the section by faulting is possibly seen, although the amount is unknown. Apart from parts of the above mentioned section, this sequence differs from any other seen in the Stinchar Limestone Formation. Points of difference are:

(i) Sandstones form a considerable proportion of the exposed sequence, as part of the Member.

(ii) At various levels in the succession, rubbly, possibly redeposited limestones, Plate 4:25, Fig. 2, attain considerable thicknesses. As with the Brochloch limestone breccias the clasts, if such they are, occur in a silty fine sand matrix and similarly a wide variety of carbonate lithologies are seen. Clast sorting is very poor, sizes ranging from granule to small cobble rounding is also poor, most clasts being highly irregular in outline, Plate 4:25, Fig. 3.

The origin of these rubbly limestones is not entirely certain, as extensive compaction and associated pressure solution prevents the recognition of abraded, clast or gradational, nodule, margins. Despite this, the mixture and variety of 'clasts' is thought to

Figure 4.6



MEASURED SECTION DUPIN(2) BURN

indicate a depositional rather than diagenetic origin and the term clast is favoured.

The sequence itself can also shed light on the origin of the limestones. The sandstone units in the Dupin sequence are poorly stratified, and lack any current cross stratification. In view of this it is felt unlikely that deposition occurred in either an offshore sandwave or nearshore, intertidal environment; the complex primary sedimentary structures thought by Walker (1978), and Reading (1978) to typify such environments not being present. An alternative environment in which these sands may have been deposited is a tidal channel. Deposition in such a setting could further account for the facies change seen between these localities and the Dupin Glen section. Sand would be supplied either by effluent discharge or resedimented from beach zones during storm events. The lack of primary sedimentary structures in these sands may be the result of intense bioturbation, recorded from present day tidal channels by Reineck and Singh (1976) and Reading (1978). In the context of a possible tidal channel environment the alternation between clastic and carbonate deposits will result from the repeated lateral migration of the channel. Sands may represent within channel deposits, bedded limestones, off-channel and the rubbly limestones, channel margin deposits. Similar facies patterns have been described from modern and ancient deposits as outlined in section 4.3.3.

Shalloch Hill

South west of Dupin, representatives of the Stinchar Limestone Formation outcrop in a small quarry on the north side of Shalloch Hill (NX29 2205 9340). The exposure is highly faulted making it impossible to determine any meaningful depositional sequence. Williams (1962) determined this sequence to be equivalent to the upper part of the Limestone Formation in the type section. Whilst no information on the depositional environment of these rocks can be gained by study of the stratification sequence, petrographic data indicates a facies different from those previously encountered. The major petrographic features of the wackestones and oncolitic fine sands that dominate the outcrop are summarised in Plate 4:26 and captions. The abundance of concentrically laminated oncolites (see

Plate 4.26

Figure 1.

Girvanella skeletal oncolites and 'chips', broken fragments of skeletal oncolites or stromatolites, in a silty very fine sand matrix.
Thin section, SHQ/4/80, plane polarised light.

Figure 2.

Detail, showing abundant fragments of Girvanella skeletal stromatolites. The Girvanella filaments are densely packed and tightly entwined around each other in a manner similar to that seen in situ algal mats elsewhere in the Formation.
Thin section, SHQ/4/80, plane polarised light.

Plate 4.26

Figure 1

4mm

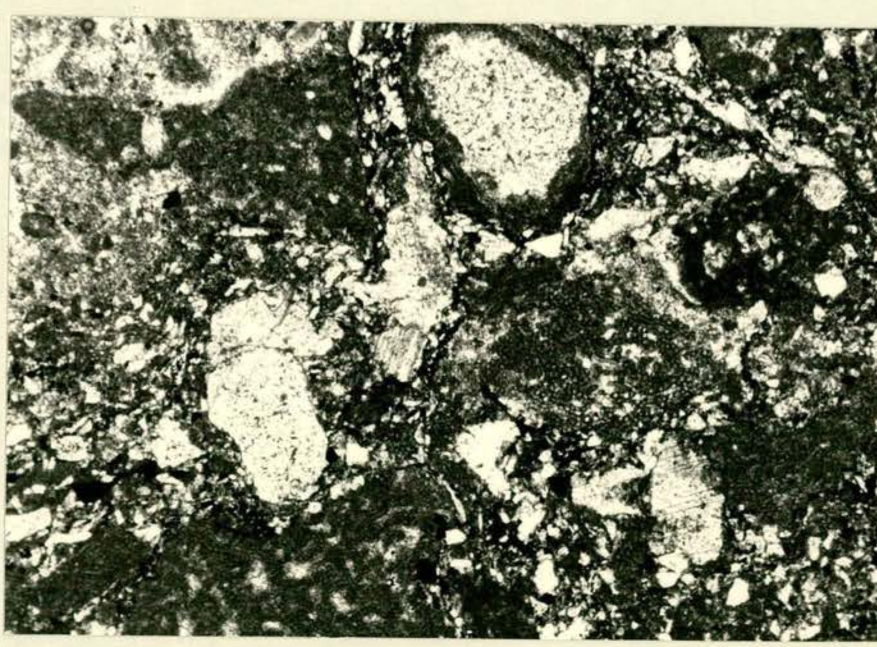


Figure 2

0.75mm

section 4.5.4), large lithoclastic grains and a fine to medium sand matrix to the larger carbonate clasts indicate an environment of consistently higher energy than most of the Formation. In addition to the oncolites, algal chips, Plate 4:26, Fig. 3, fragments of either skeletal stromatolites or skeletal oncolites (Riding, 1976) are a second, abundant algal grain type. In either case the breakage of what were probably quite resistant particles must reflect turbulent water conditions. Whilst no definite depositional environment is proposed due to the small amount of evidence available, it is felt that these deposits most probably accumulated in a beach or nearshore environment. The outcrops of Ballantrae Complex lavas on Shalloch Hill might in this case represent a formerly emergent area, and not just an up-faulted block. Furthermore the presence of a shoreline in this position would explain the distribution of the Stinchar Valley Member sheet sandstones, although it may also be possible that these could have been derived from sands in the possible tidal channels at Dupin.

4.5 Tormitchell Member

4.5.1 Introduction

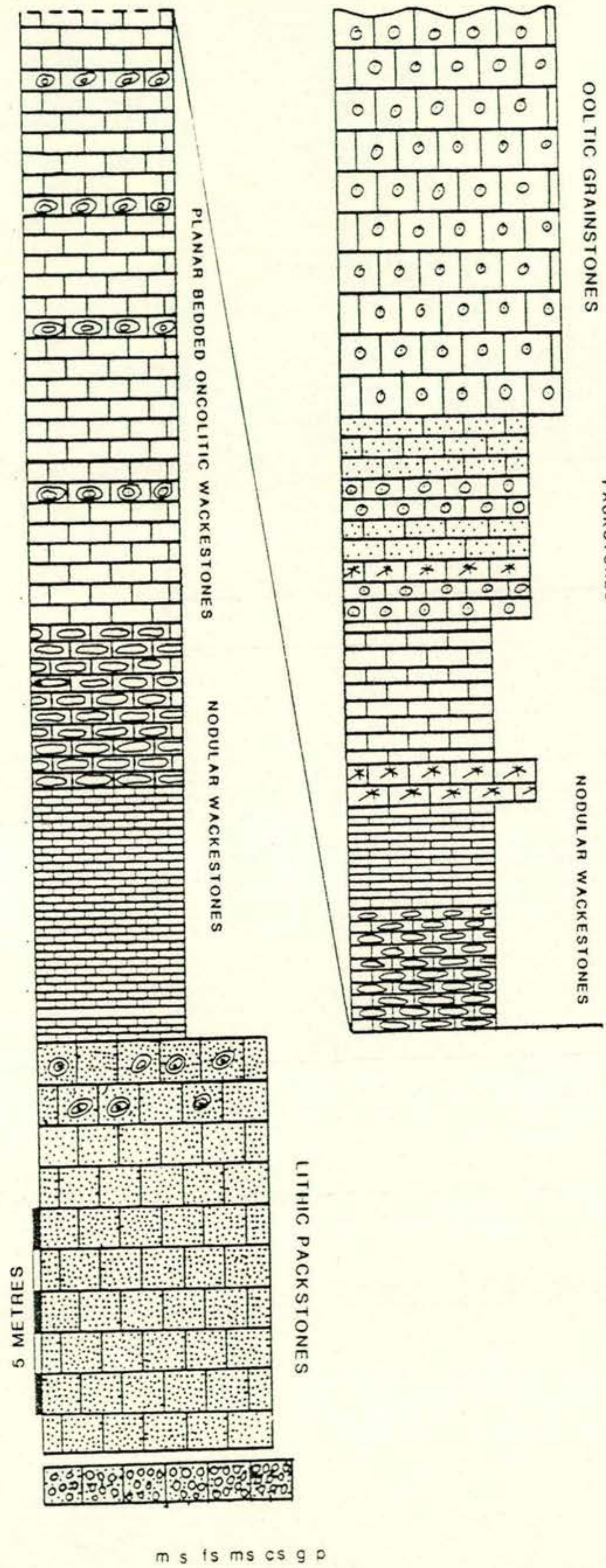
To the north of the Water of Assel, separated from the Brochloch and Dupin localities by the Dupin fault complex, major outcrops of the Stinchar Limestone Formation occur only in the working quarry at Tormitchell (NX29 2325 9435). The Base of the Limestone Member sequence is marked by a high angle fault, the Tormitchell Thrust of Williams (1959), which brings the carbonates into contact with turbidites assigned to the Ardwell Group (Williams, 1962), which have yielded graptolites indicative of a middle to upper Caradoc age. The sequence displayed in the quarry sections is one of the thickest developments of the Limestone Formation, and shows considerable variation in lithology and facies. In addition to its sedimentological significance this locality is also important as the type locality of the fossil cyanophyte Girvanella.

4.5.2 Description of Facies

Figure 4:7 shows a graphic representation of the Tormitchell sequence along the E. face of the quarry. Three sub-divisions, informally termed facies, Chapter 2, can be made on the basis of

Figure 4.7

MEASURED SECTION EAST FACE OF TORMITCHELL QUARRY



lithology, bedding characteristics and environmental significance although variation within a given facies may be appreciable.

Facies A: forms the lowermost 10-12 metres of the Member. Pebble conglomerates occur at the base of the unit and contain well rounded and sorted clasts of red, green and black chert, with some vein quartz. Above the conglomerates the rest of the facies is composed of lithic packstones, Plate 4:27, Fig. 1. Coarse, sand and granule size, particles of predominantly basaltic lithologies are set in a matrix of recrystallised lime mud. The abundance of skeletal grains is low in the lowermost beds of the facies. With an upwards decrease in lithic grain size and abundance crinoidal and oncolitic grains become increasingly important.

Petrography

Lithic and crystalline material, basalt, chert, feldspars and quartz, derived from the local Ballantrae Complex basement, constitute 30-70% of grains present, the percentage decreasing to the top of the unit. These grains are variably, but generally, well rounded, and may also serve as nuclei for oncolites and ooids (Plate 4:27, Fig. 2). The main carbonate grains present, in order of abundance are: ooids, micritic lumps, crinoidal debris, algal lumps and grains of *Nuia*. A more diverse assemblage of carbonate grains appears towards the top of the unit, foraminiferids, cyclocrinitid algae, dasycladacean algae, oncolites and gastropods all being abundant. A micritic matrix may be present although generally neomorphosed to microspar, no cement fabrics were observed.

Facies B: The lithic packstones of Facies A pass via a very thin transitional zone into the wackestones of Facies B. As shown in figure 4:7, a wide range of different bedding types occurs within this 30 metre thick unit. Nodular limestones occur at the base and top of the facies, these are in general more fossiliferous than the planar, thick bedded central part of the unit. Algae *Girvanella* and an unidentified cyclocrinitid, Plate 4:27, Fig. 3, are particularly abundant, as are gastropods of various types, the foraminiferids *Saccaminopsis* and *Thuraminoides*, and crinoid fragments, Plate 4:27, Fig. 4. Nodules are separated by clay seams, along which extensive

Plate 4.27

Figure 1.

Disrupted bedding in lithic grainstones of Facies A, Tormitchell Member. The bedded units are buckled, perhaps slightly slumped. Tape measure, 37cm long. Loose block, Tormitchell Quarry.

Figure 2.

Compacted lithic, oolitic, grainstone, Facies A, Tormitchell Member. Compaction is indicated by the presence of strain shadows, arrowed a. Carbonate grain types present include ooids (b) and micritic 'lumps' (c) of indeterminate origin. The rock is calcite cemented. Thin section, TM/63/79B, plane polarised light.

Figure 3.

Cyclocrinitid alga, probably Mastopora sp., Tormitchell Member. Lower part of Facies B.

Figure 4.

Fragment of unidentified small crinoid. Lower part of Facies B, Tormitchell Member.

Plate 4.27

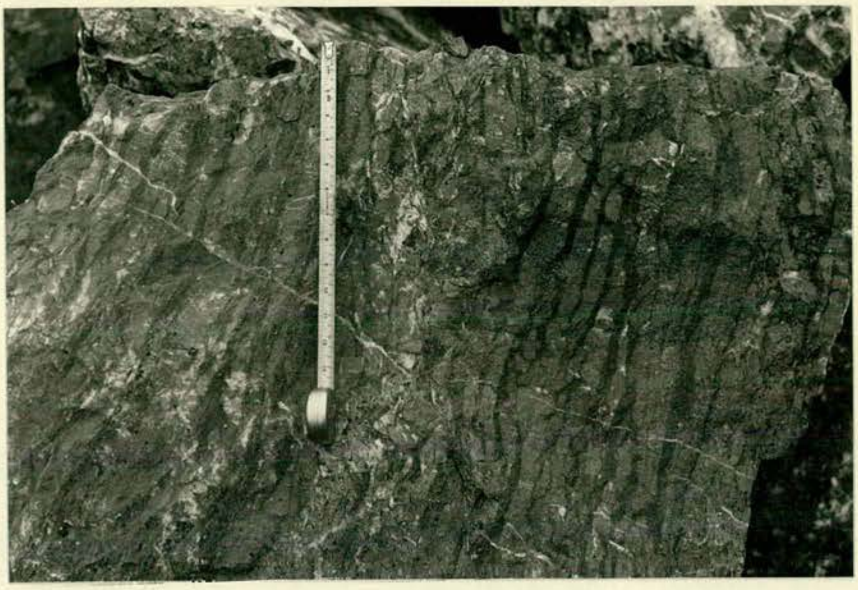


Figure 1

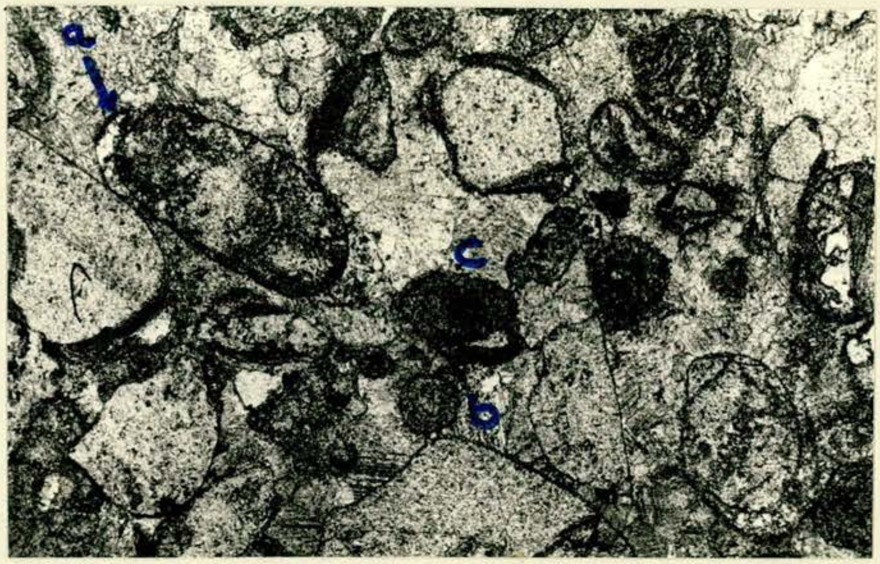


Figure 2

0.5mm

Figure 3

0.5cm

Figure 4

3.5mm

pressure solution and carbonate veining has taken place.

The central part of the Facies B sequence is made up of relatively thickly bedded, dark, lime mudstones and wackestones with packstone horizons developed within many of the bedded units. Silty clay interbeds are well developed, 3-4cm in thickness, and are gradational into both the underlying and overlying limestone beds.

The intra-bed packstone and wackestone horizons occur as well defined, laterally discontinuous layers 5-7cm thick and up to 1m in lateral extent, generally but not always, towards the middle of the bedded unit, Plate 4:28, Fig. 1. Oncolites and large fragments of gastropod shell are the most abundant skeletal grain type in these horizons. Well defined, relatively sharp bases and irregular upper margins are typical. Size sorting is poor, foraminiferid tests also occur within these horizons. The uneven distribution of coarse skeletal material throughout a given bedded unit, and the sharp, well defined base to the bioclastic horizons suggest that these are the result of a single, high energy event. The genesis of bioclastic carbonate horizons in muddy (terrigenous or carbonate) shelf environments has been discussed by various authors (Brenner and Davies, 1973, Specht and Brenner, 1979, Kreisa, 1981). All these workers interpret such deposits as the result of sediment winnowing during the passage of storm waves, having higher energy and lower wave base than normal. The bioclastic or coquinoid horizons are therefore essentially lag deposits. The lime mud that now occupies the interstices of what is probably a self supporting framework is secondary in that it probably settled out from suspension, after the storm had passed. A similar process, related to the passage of swell-induced bottom currents, is invoked by Powers and Kinsman (1953) to account for the occurrence of well sorted shell horizons in Recent sands of the continental shelf off Chespeake Bay, U.S.A.

It is worth noting that these storm deposits do not occur in every one of the thick limestone beds, not do they occur in the silty clay interbeds. These observations indicate that the storms producing the shell horizons were infrequent events, and were genetically unconnected to any influx of fine grained terrigenous debris into the area of deposition.

Towards the top of the facies, bed thickness decreases and a thin horizon (2m) of nodular limestones is developed. Above this a 0.75m thick horizon of lensoidally bedded crinoidal packstones that may represent megaripples of skeletal sands, although internal rippling is absent, possibly as a result of bioturbation. The final unit in the Facies B sequence is 3.5m of nodular and thinly bedded algal wackestones identical to those seen at the base of the facies.

Petrography

The biogenic components present in this facies are of the same types as those already described in section 4.2.4. The abundance of certain grains is, however, noticeably different. Oncolites, constructed by Girvanella and various non-filamentous algae, see section 4.5.3, are particularly abundant in the nodular horizons at the top and base of the facies. In the central, well bedded, part of the sequence, oncolites occur almost exclusively in the storm lag horizons already discussed. A diverse and abundant gastropod fauna shows the same distribution pattern as the oncolites, both broken and complete shells often serving as oncolite nuclei. Trilobite, orthocone nautiloid, and particularly brachiopod remains are scarce, even when compared with localities in the Stinchar Valley Member. Calcite cements infilling cavities in the various fossils present are generally of clear, equant calcite. Only rarely are dusty, botryoidal faintly fibrous cements (Plate 4.28, Fig. 2) here interpreted as a neomorphic alteration of a former fibrous seawater derived cement, seen in this facies.

Facies C: above the Facies B wackestones, oolitic and crinoidal packstones and grainstones form the remainder of the Tormithcell Member sequence. As shown in Fig. 4:7 the basal five metres of the facies is made up of interbedded oolitic and peloidal grainstones and packstones. Size sorting of the skeletal grains is good. Ooids are generally rounded, having laminae that may reflect either algal encrustation or micrite envelope formation as a result of algal or fungal boring. Lithic grains, quartz,feldspar, are moderately abundant, and are concentrated in irregular layers, either solely as a result of pressure solution or this latter process acting on preexisting sand laminae.

Plate 4.28

Figure 1.

Oncolitic storm lag deposit. The poorly developed Girvanella oncolitic coatings are seen as thin, dark, encrustations on gastropod shell debris. The base of the unit is sharp, well defined.

Cut surface, TM/16/80, central part of Facies B, Tormitchell Member, Tormitchell.

Figure 2.

Detail showing faintly preserved inclusion rich botryoids (a) of calcite cement lining the inner surface of a foraminiferid test. The central areas of the cavity are occupied by clear spar. Both cements and the test wall are neomorphosed, with accompanying loss of primary structure.

Thin section, TMONC/2, plane polarised light.

Figure 3.

Massive oolites of Facies C, Tormitchell Member, (a) overlying the thinly bedded wackestones (b) typical of the upper part of Facies B. Between the two is the thin sequence of lithic packstones that denotes the transition from one facies to the other.

South face of Tormitchell Quarry.

Plate 4.28

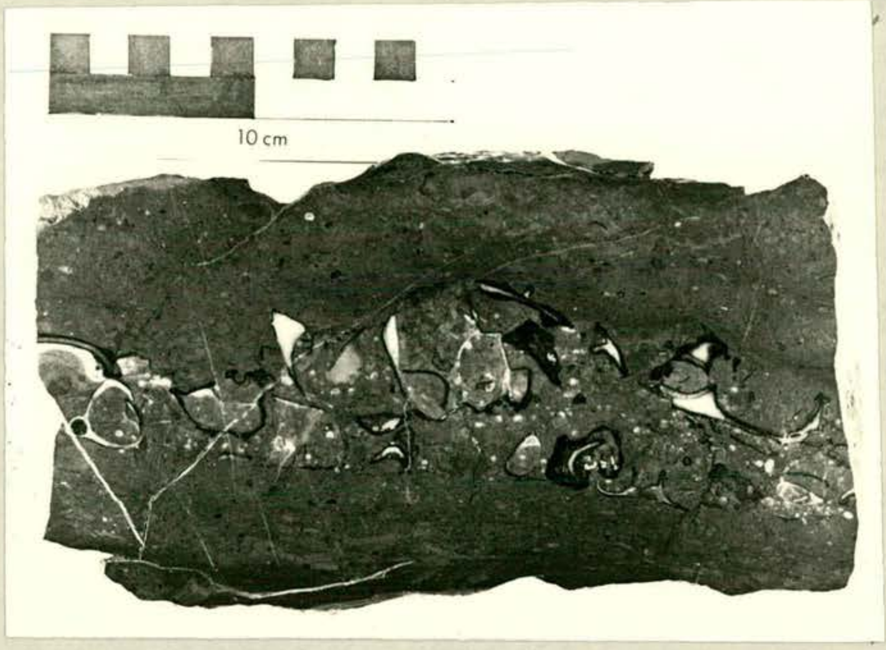


Figure 1

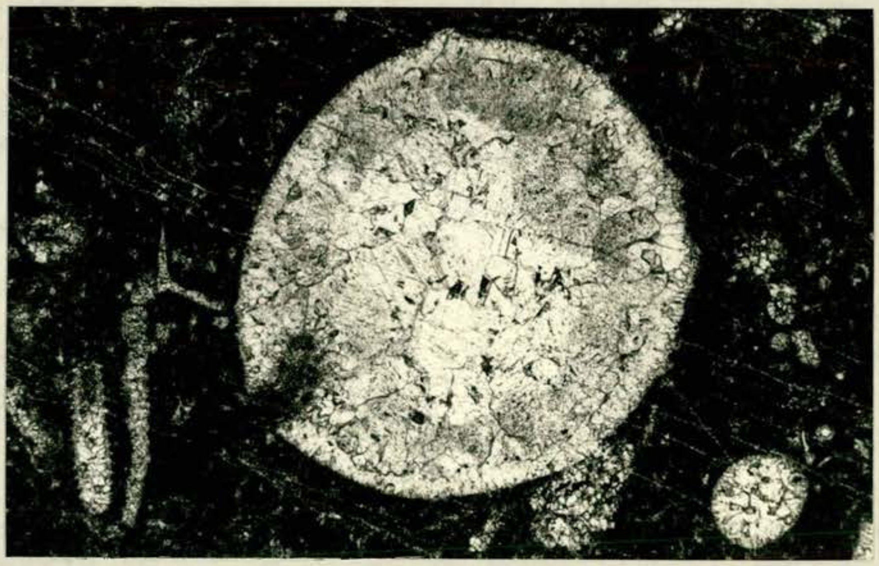


Figure 2

0.6mm

Figure 3

Above the basal, lithic packstones the sequence continues with 10-12m of medium to coarse grained, massively bedded oolites, Plate 4.28, Fig. 3, occasionally laminated. No current cross-stratification, a feature typical of migrating, unstable oolite shoals (Wilson, 1975, Ball, 1967) is present. Rippling of the modern oolites of the Bahama Cays is most intense on the shoal crest and seaward edge, but is almost absent on the lagoon-wards edge, where a dense cover of Thalassia testudinarium strongly inhibits movement of the grains (Newell et al. 1959, Newall et al., 1960). Rippling of parts of oolite shoals may also be inhibited by the presence of a subtidal algal mat (Bathurst, 1967). In areas of shallow water carbonate deposition around the Bahamas, sub-tidal algal mats are present over a wide variety of skeletal and oolitic sand substrates, being absent only from those areas, such as tidal channels and mobile shoal surfaces, where the degree of substrate instability prevents colonisation (Bathurst, 1976). The preservation potential of these mats is low, the algae providing nourishment for infaunal organisms (Bathurst, 1976). Thus ancient carbonate sands may show no sign of current transport and may be poorly sorted, as a result of the presence of an algal mat. Within the Tormitchell Member, evidence for algal colonisation of the carbonate sand substrate is provided by the presence of grapestone lumps and algal chips with parallel laminated Girvanella filaments (see section 4.5.3).

Facies C: Oolitic packstones and grainstones

The lower horizons of the facies are oolitic, lithic and crinoidal, Plate 4:29, Fig. 1, packstones. Lithic material is fine grained, moderately angular and dominantly quartzo-feldspathic. Oolitic or thin oncolitic grain coatings are common, Plate 4:29, Fig. 2. The lime-mud matrix is neomorphosed to coarse microspar or spar. In the upper, oolitic part of the facies ooids, algal (Girvanella) lumps, peloids and grapestone lumps (Illing, 1954) are the major grain types present, Plate 4:29, Figs. 2 & 3. Ooids, the most abundant grain type, possess faint, poorly radial structures and thick, dark, micritic, concentric laminae. The micritic laminae most probably formed as a result of the boring activity of fungi and algae, eventually forming a micrite envelope in the manner proposed by Bathurst (1966). Organic material is an important component of Recent ooids, blue-green and green algae both being present (Newell

Plate 4.29

Figure 1.

Crinoidal/peloidal/oolitic packstone from the zone transitional between facies B and C , Tormitchell Member.

Thin section, TM/1/79B, plane polarised light.

Figure 2.

Oolitic and oncolitic grain coatings in Facies C oolites. The clear spar in the intergranular areas can be seen to line pores (in area arrowed) but is neomorphosed and lacks any distinctive primary features.

Thin section, DI/1/82, plane polarised light.

Figure 3.

Ooids and peloidal, micritic lumps in Facies C, oolitic grainstone. The ooids have dominantly radial structure, with coarse concentric micritic laminae also preserved.

Thin section, TM/51/79, plane polarised light.

Figure 4.

Amalgamated ooids in Facies C oolites, the grains (arrowed) are bound together by micrite perhaps of algal origin and may be comparable to present day grapestone.

Thin section, TM/51/79, plane polarised light.

Plate 4.29

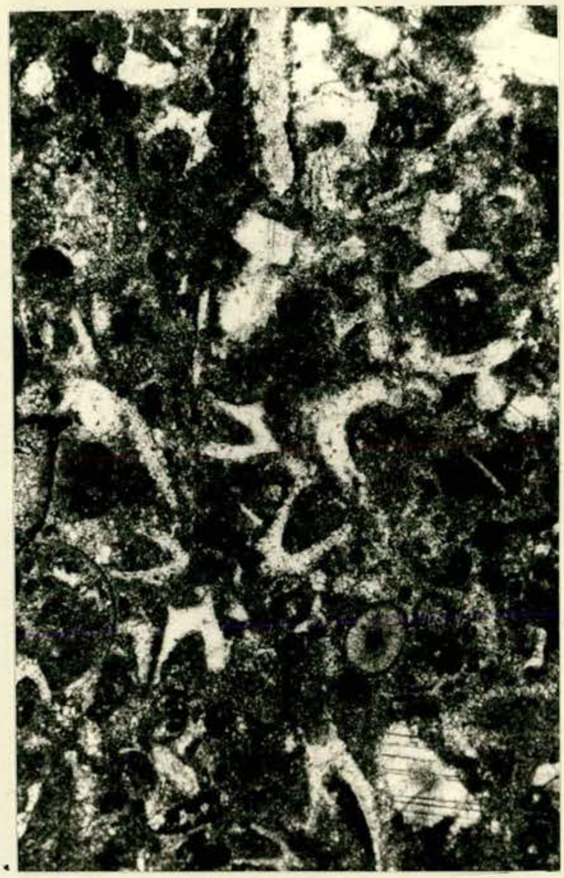


Figure 1

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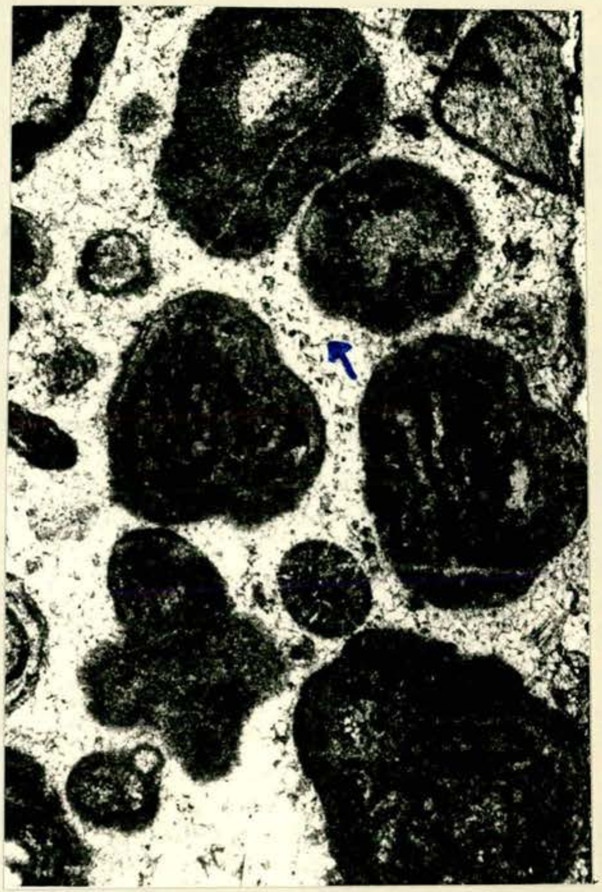


Figure 2

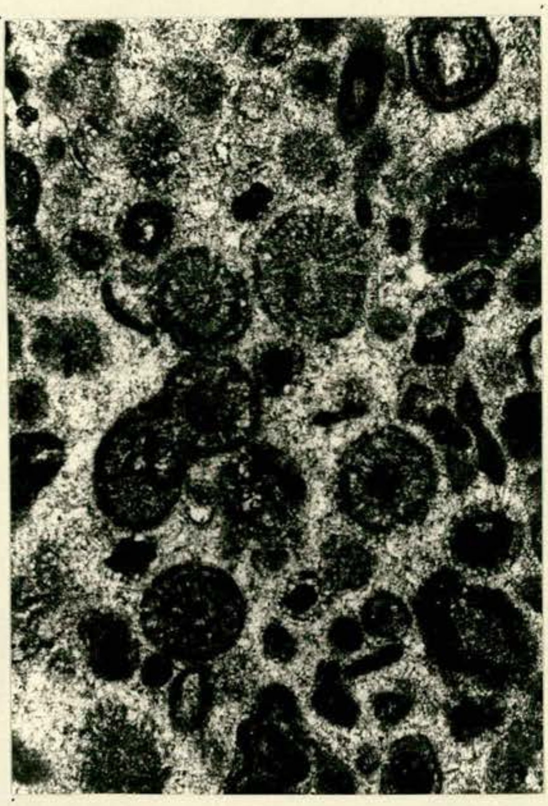
0.8mm

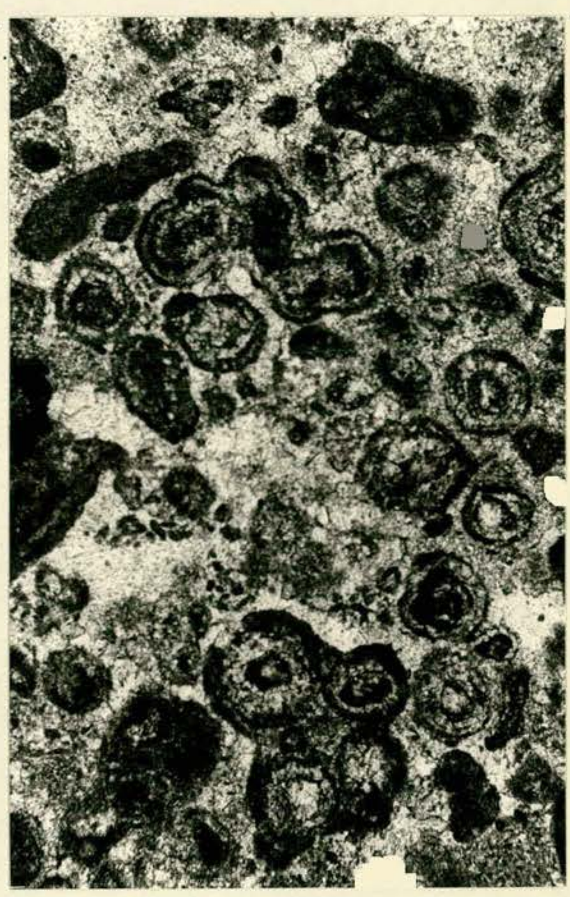
Figure 4

1mm

Figure 3

1mm





et al., 1960) as well as organic films on the external surfaces, Simone (1980). Grapestone lumps result from the cementation either directly, by aragonite precipitation (Kendall and Skipwith, 1969) or by algae and foraminiferids (Winland and Matthews, 1974) of ooids, micritic lumps and other grains of lime sand (Bathurst, 1976). The sub-tidal algal mats that stabilise areas of present day grapestone accumulation (Bathurst, 1976) may be represented in the Tormitchell Member by the numerous algal lumps or chips of parallel aligned Girvanella filaments. The micritic, cryptocrystalline lumps or peloids seen in the Tormitchell oolitic grainstone may be comparable to the rounded, polygenetic grains of mud-sized carbonate, described by Ginsburg and James (1974) as forming in less than 10m water depth.

4.5.3 Tormitchell Algae

Introduction

The Tormitchell quarries have long been known as the locality from which Nicholson and Etheridge first described the fossil alga Girvanella in 1878. In addition to abundant Girvanella, Nuia and a cyclocrinitid green alga are also present. It is, however, the variety of Girvanella growth forms that are the most interesting and informative feature of the Tormitchell flora, this being the type locality for the genus.

Girvanella growth forms and their significance

The most readily observable Girvanella growth forms are the large oncolites seen concentrated into storm lags in Facies B. In addition various other, less abundant and less striking, but equally important forms are seen, often being restricted to a particular facies.

Oncolites

Facies A: large, 2.5-3cm to medium, 1-2cm, sized, circular to slightly oblate in section, moderately regular outer margin. Nucleus of carbonate, skeletal or non-skeletal, lithic or crystal grains. Internal fabric poorly preserved, faintly evently laminated when seen in weathered surfaces, filaments not discernable in thin section.

Facies B: generally large, 2.5cm, dark brown and grey weathering, unevenly laminated growths, Plate 4:30, Figs. 1 & 2. Nuclei consist of either skeletal fragments, usually gastropod shells, Plate 4:30, Fig. 2, or wackestone intraclasts, Plate 4:30, Figs. 1 & 3. Internal structure is complex, irregular and well preserved. Filamentous, *Girvanella* and non-filamentous, Plate 4:31, Figs. 1 & 2, algae are both present. In addition, areas of micrite or microspar, Plate 4:31, Fig. 2, may represent either evidence for non-calcareous algae or small amounts of sediment incorporated into the growth between periods of movement. *Girvanella* filaments are, in general, orientated outwards from the nucleus, Plate 4:31, Fig. 3. Filaments are loosely entwined and show no sign of alignment. Internal laminae reflect the complexity of external outlines, and may represent either a particular type of encrustation or a period of erosion of the growth, Plate 4:31, Fig. 4.

Algal mats

Felted, flocculose (Plate 4:32, Figs. 1 & 2) mats occur throughout Facies B. These consist of loosely intertwined, flexuous filaments, in places seen to twist around each other, giving a cabled appearance, Plate 4:32, Figs. 1 & 2. In vertical section the felted mats are seen to develop from a basal layer of tightly intertwined near horizontally orientated filaments, in a manner similar to the growths described from the Stinchar Valley Member and the present day growths described by Golubic (1973) and illustrated in Fig. 4:3.

Algal chips

Algal chips, Plate 4:32, Fig. 3, are a volumetrically and ecologically important grain type in Facies C. They consist of well defined grains of dens packed *Girvanella* filaments. The filaments may be disorganised, spaghetti-like or organised, the filaments being aligned parallel to each other (Plate 4:32, Fig. 3). The internal structure of the latter grain type is similar to that reported from present day sub-tidal mats dominated by *Lyngbya truncicola*, described from Abaco, Bahamas by Neumann et al. (1970) and those composed of *Schizothrix calcicola* and *Oscillatoria submembranacea*, described by Gebelein (1969) from Bermuda. The algal chips are thought to result from the erosion and breakup, by both mechanical and biological mechanisms, of mats that once served to stabilise the oolite sands. More loosely entwined filament bundles, Plate 4:32, Fig. 4, occur throughout Facies B, these may have been formed in a similar manner from mats of a different internal organisation, or containing different forms of filamentous alga.

Plate 4.30

Figure 1.
Large, complex, oncolite composed largely of <u>Girvanella</u> but also containing growths of non-filamentous algae (arrowed). The algae are encrusting an intraclast of peloidal wackestone. Note the complex and irregular laminae.
Thin section, TMONC/7, plane polarised light.

Figure 2.
Complex <u>Girvanella</u> oncolite with uneven internal laminae. The nucleus consists of a gastropod shell fragment and adhering wackestone. Cavities occurring beneath the gastropod shell (a) are infilled by both internal sediment and calcite cement.
Thin section, TNONC/3, plane polarised light.

Figure 3.
Detail showing rounded surface of wackestone intraclast now seen as a nucleus to a <u>Girvanella</u> oncolite.
Thin section, TMONC/11, plane polarised light.

Plate 4.30

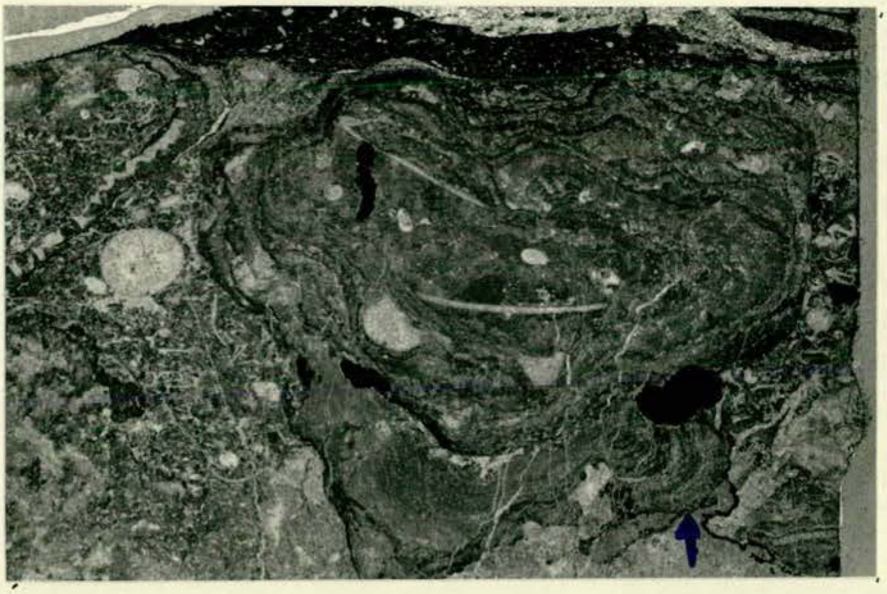


Figure 1

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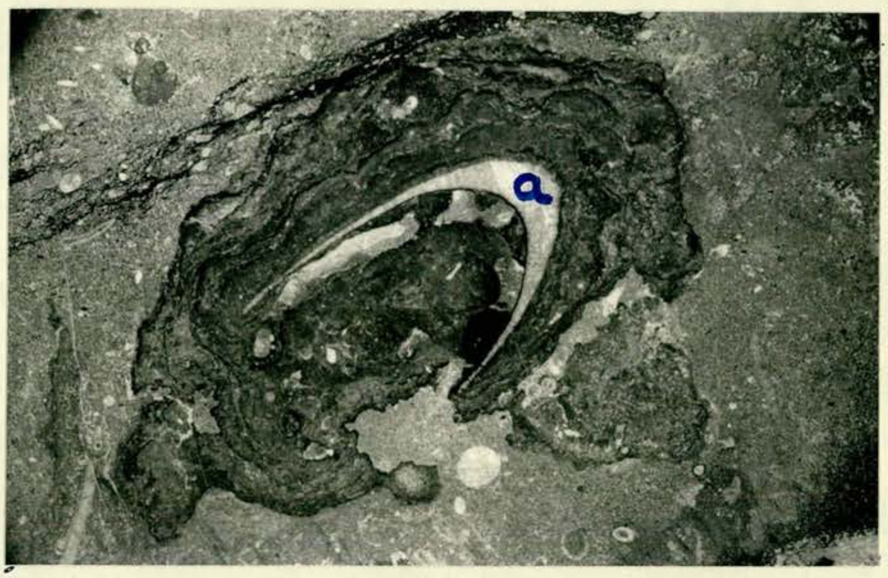

Figure 2

6mm

Figure 3

1mm

Plate 4.31

Figure 1.
Detail, showing small stromatolitic growth consisting of non-filamentous algae. The growth occrus as part of a Girvanella dominated skeletal oncolite.
Thin section, TMONC/6, plane polarised light.

Figure 2.
Detail, showing non-filamentous algae (A) encrusting Girvanella oncolite. The non-filamentous alga is of a different type to that shown in the previous figure. The alga lacks any internal lamination.
Micritic sediment incorporated into the growth is seen at (B).
Thin section, TMONC/3, plane polarised light.

Figure 3.
Girvanella filaments in skeletal oncolite. The filaments show no particular relationship to the surface of encrustation (E).
Thin section, TMONC/3, plane polarised light.

Figure 4.
Complex internal fabric in Girvanella oncolite. The shelter cavity (s) formed beneath the original growth, both were later upmoved and the algal laminae in the area (A) developed.
Thin section, TMONC/3, plane polarised light.

Plate 4.31

1mm

Figure 1

Figure 2

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Figure 3

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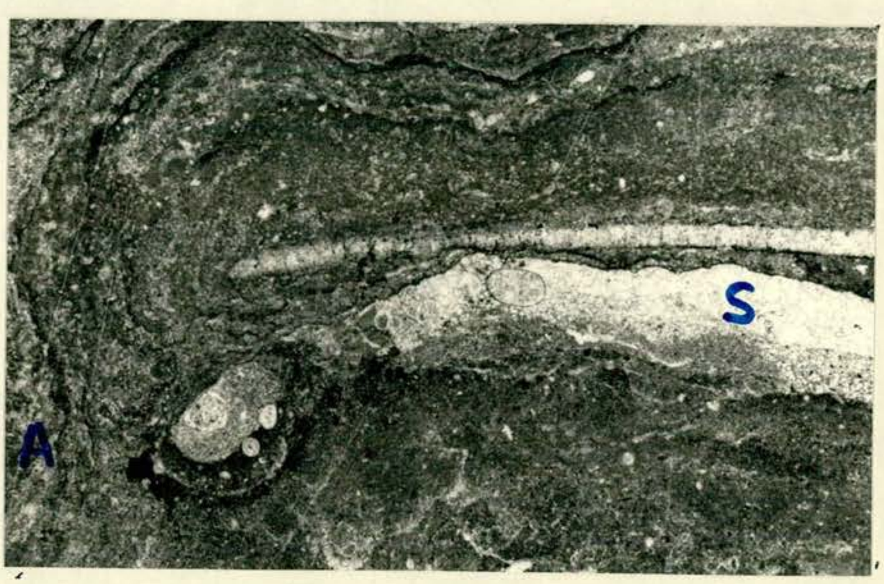

Figure 4

Plate 4.32

Figure 1.
Felted, flocculose, stromatolitic mat composed of Girvanella filaments cabling around each other. Areas between the filaments are occupied by neomorphosed lime muds.
Thin section, TMONC/3, plane polarised light.

Figure 2.
Cavity developed within Girvanella mat. The filaments at (A) show the cabled growth form.
Thin section, TM6/79A, plane polarised light.

Figure 3.
Dense, micritic algal chip in Facies C oolite.
Thin section, TM/55/79, plane polarised light.

Figure 4.
a) Scanning electron micrograph of small pyritised bundle of Girvanella filaments.
b) Photomicrograph showing similar growth form of Girvanella.
Thin section, TMONC/2, plane polarised light.

Plate 4.32

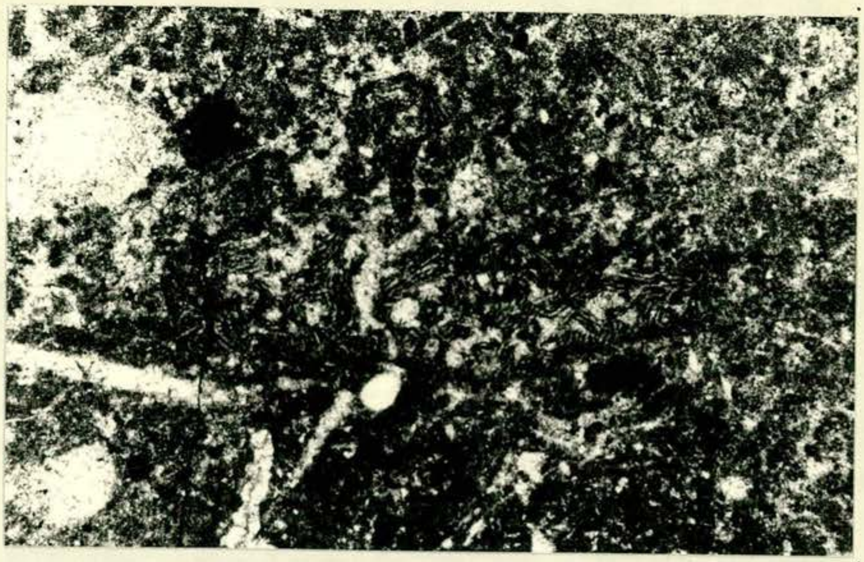

Figure 1

Figure 2

Figure 3

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Figure 4

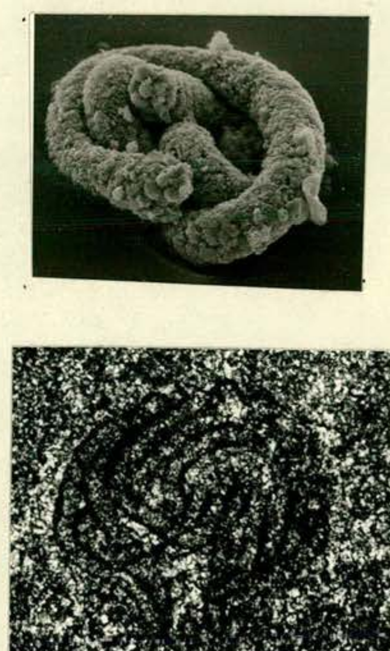

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Plate 4.33

Figure 1.
Skeletal stromatolite composed solely of Girvanella filaments.
Thin section, TM/59/79B, plane polarised light.

Figure 2.
Detail of the above growth showing the development of a fenestral fabric within the stromatolite.
Thin section, TM/59/79B, plane polarised light.

Figure 3.
Oncolite from oolitic/oncolitic grainstone horizon at Aldons Quarry.
The Girvanella filaments are aligned parallel to the surface of encrustation.
Thin section, AL/X/79, plane polarised light.

Figure 4.
Detail of high energy Girvanella oncolite showing clearly the parallel alignment of the filaments relative to the surface of encrustation.
Thin section, AL/X/79, plane polarised light.

Figure 1

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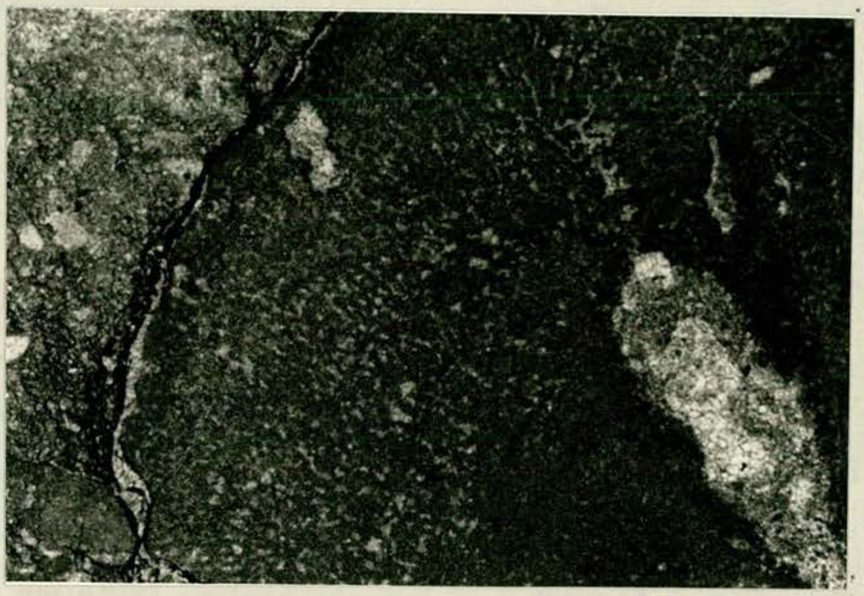

Figure 2

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Figure 3

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Figure 4

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Skeletal stromatolites

Girvanella skeletal stromatolites (Riding, 1977), Plate 4:33, Figs. 1 & 2, are a relatively rare, but significant growth habit in Facies B, which has not been previously reported. These are upstanding, apparently self-supporting structures composed of moderately flexuous but evidently organised filaments of Girvanella, Plate 4:33, Fig. 2. Fenestral fabrics occur in the more loosely packed parts of the growths, Plate 4:33, Fig. 2. No attempt will be made at the moment to interpret these growth forms, they differ so markedly from any other occurrence. The possible taxonomic significance of these findings is commented on in the following discussion. In addition to the above modes of occurrence, Girvanella filaments also occur as small, isolated bundles of filaments already interpreted as broken up algal mats.

Discussion

Oncolites have long been recognised as a distinctive product of algal growth, usually interpreted, by analogy with comparable present day growths as having formed in water depths of 0-6m (Ginsburg, 1960, Kinzly-Moore, 1979). Few attempts have, however, been made to recognise any subtle variation in oncolite structure and from these observations draw environmentally significant conclusions. Fuchtbauer (1968), Peryt and Peryt (1975) and Peryt (1977) interpret Upper Permian "tender" oncolites, characterised by very delicate, wavy laminae, as indicative of water depths of more than 30m, in Zechstein "basinal" limestones. On the basis of the evidence presented by these authors, however, these growth forms could as easily be interpreted as the product of decreased turbulence in a shallow water setting.

In the Tormitchell Member, Facies B is interpreted as a shallow water lagoon, with the floor within storm wave base (section 4.5.4). Furthermore, this proposed lagoon was sufficiently shallow for Girvanella mats and dasycladacean algae to grow. Present day subtidal algal mats are most abundant in water depths of less than 18m (Ginsburg, 1960) and present day dasycladacean algae are most abundant in water depths of less than 15m (Wray, 1976). The presence of these and other indicators of shallow water conditions in the Tormitchell deposits is felt to provide a reliable control over the maximum depths at which the oncolites developed. In this situation a general lack of turbulence is indicated by the highly irregular internal laminae and outer margins of the Facies B. oncolites. In contrast Girvanella oncolites found in grainstone units of the Stinchar Limestone Formation, deposited in a higher energy regime, possess regular, near concentric laminae, Plate 4:33, Fig. 3. This internal structure is mirrored on a microscopic scale by the algal filaments, aligned parallel to the surface of encrustation, Plate 4:33, Fig. 4. This particular microstructure may have resulted either from removal of filaments having any other orientation, by abrasion, or an actual adaptation on the part of the algae to a more stressful environment.

In taxonomic terms the significance of the felted, flocculose and cabled growth forms may be considerable. In all cases the species of Girvanella found to constitute the growths in question was G. problematica, the type species of the genus, as distinguished on the basis of filament size only according to the diagnosis of Wood (1957). As noted by various authors, e.g. Edhorn (1979), there are too many species of Girvanella based upon slight differences in filament sizes or configuration. Many of the growth forms described herein are markedly different, in terms of filament configuration, from previously described species. It is felt however that this variation may reflect not a number of differing species, but rather the response of an adaptable and variable organism to differing environmental challenges. Whilst the cyanophyte affinities of Girvanella are no longer in doubt since the discovery by Riding (1977) of a modern analogue, Monty (1967) and Riding (1975) advise that whilst an affinity at generic level with the Oscilliatoriaceae is likely, other present day forms may be equally comparable. The similarity between the Girvanella mats illustrated throughout this thesis, and present day Oscilliatoriacean mats is felt to be a significant indication of affinity. Furthermore, the present author feels that the study of growth forms and habits advocated by Danielli (1981) is likely to prove a most useful tool in gaining further understanding of a particularly fascinating microfossil.

4.5.4 Environmental interpretation of the Tormitchell Member

Facies A is interpreted as a shallow marine, beach and or subtidal sand body, deposited on a Ballantrae Complex basement from which the sequence as a whole has subsequently become detached during faulting.

Throughout the facies detrital content decreases with concomitant increase in skeletal carbonate content. This pattern may well have developed in response to shoreline retreat during transgression of the Kirkland Formation and Ballantrae Complex Basement.

Facies B is interpreted as a shallow lagoonal deposit. Sediment accumulated below fair weather wave base,but was sufficiently shallow to be disturbed by sporadic storm events. The lack of bottom turbulence is reflected in the structure of Girvanella oncolites and may have resulted from protection of the lagoonal area by a migrating oolite shoal seen in Facies C. The transition from Facies B to Facies C, a series of lithic, oolitic and crinoidal packstones, may represent a series of spillover lobes derived from the oolite shoal and the areas immediately to the leeward, where filter feeding organisms such as crinoids may have found sufficient turbulence to survive.

4.6 Unassigned localities

Aldons

In dissused quarries near High Aldons (NX18 1970 8960), Stinchar Limestone Formation carbonates and an associated, basal clastic unit unconformably overly pillow lavas of the Ballantrae Complex. The clastic sediments fine upwards from pebble conglomerates, to sands and eventually pass upwards into limestones with scattered pebbles. Lower horizons in the carbonate sequence may have slumped or been disturbed. The remainder of the limestone sequence consists of variably muddy wackestones and interbedded grainstones. The uppermost horizons of the Formation became increasingly muddy and pass into a thin unit of sheared mudstones with carbonate nodules, the local development of the Benan Formation Mudstone Member. Though thrust over the mudstones the Conglomerate Member occurs in its correct stratigraphic position. A wide variety of Girvanella growths occur in abundance throughout the sequence as does Nuia.

The Aldons succession is separate from the main area of carbonate deposition within the Formation, the Stinchar and Assel valleys, and, apart from a broad lithological similarity, has little in common with the type sequences. No interpretation, other than that a shallow marine environment is represented, is attempted.

Colmonell and Bougang

12.5 kilometres S.W. of the type locality of Benan Burn, in quarries and stream sections near Craigneil Castle (NX28 147 853), sediments assigned by Williams (1962) to the Barr Group. Extensive faulting has affected most outcrops, which show little lithological similarity to those seen in the major areas of outcrop. In view of the complexity of these outcrops, their poor exposure, and the probability that they accumulated as part of a separate depositional system, they were not included in the present study.

Lendal Valley

See section 2.8.

Pinmacher and Laigh Letterpin

Sections through the above localities, reported by Williams (1962) are no longer available.

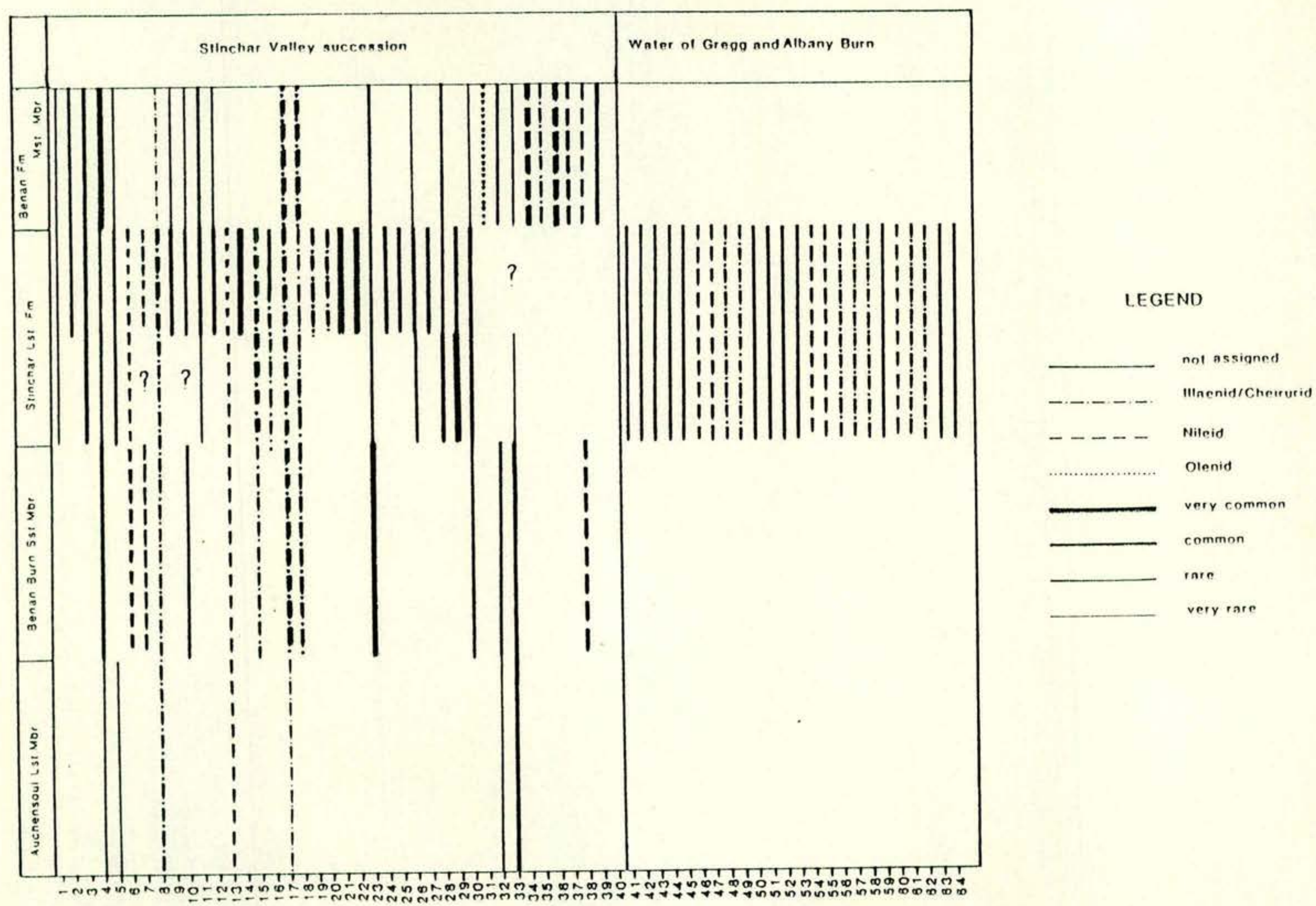
4.7 Macrofauna

Whilst the Ordovician sedimentary sequences of the Girvan area are of undoubted interest it is the fossil faunas contained within them that have in the past attracted the greatest interest. As a result of this there exists a vast literature fully describing the major groups of invertebrate fossils present. The trilobite faunas have been documented by Reed (1903-1906), Begg (1939, 1946, 1950[a], 1950[b]) and Tripp (1954, 1962, 1965, 1967, 1976, 1979, 1980), and the brachiopods by Reed (1917, 1944, 1945) and Williams (1962). In view of this the present author has not become involved in any further study of these groups.

In view of the diversity of the faunas of the Barr Group they might be thought suitable for palaeoecological studies, but fossils are particularly rare and such prospects are very limited. It is, however, possible to pursue one particular aspect of trilobite palaeoecology, using published data. Fortey (1975) during a study of Arenig-Llanvirn trilobite faunas from Spitzbergen, distinguished three communities or associations of genera, whose occurrence could be related to differing positions in a shallow to deep water gradient. Tripp (1979) has applied this community concept to the "lower" and "middle" Stinchar Valley Member at Minuntion, and concluded that the fauna at this locality was indicative of the Illaenid/Cheirurid community, thought by Fortey (1975) to have inhabited the shallowest

Figure 4.8

DISTRIBUTION OF DEPTH RELATED TRILOBITE COMMUNITIES IN THE BARR GROUP



water. Ingham (1978) using the same principle suggests that the Benan Burn Sandstone Member (confinis flags) also contain an Illaenid/Cheirurid community. The Albany Mudstones (see Chapter 6) and the Benan Formation Mudstone Member ('superstes' mudstones) are assigned to the deeper water Nileid community. Figure 4:8 shows the distribution and abundance of these communities in the Barr Group and laterally equivalent units, and suggests that Forteys community concept is indeed applicable and also the opinions of the above authors would appear to be valid. It is, however, worth noting that many of the taxa plotted in Fig. 4:8 were not included by Fortey in his associations. It is possible that consideration of these forms might alter the conclusions outlined above.

4.8 Microfauna

Bergstrom (1971) reports that the Pygodus serrus/P. anserinus conodont zonal boundary, equated with the Llanvirn/Llandeilo junction occurs within the Stinchar Limestone Formation section exposed in Benan Burn. Large samples were collected from the major Limestone Formation localities, for the purpose of extracting conodonts and thereby locating the position of this potential time line throughout the Formation. Unfortunately the conodont faunas recovered only rarely contained stratigraphically important species, and whilst the material from Benan Burn confirmed Bergstrom's findings the zonal boundary could not be located in any other section. Bergstrom (1981, pers. comm.) reports that despite fresh collecting he also has failed to collect stratigraphically important species from any other localities.

4.9 Summary

The salient features of the Stinchar Limestone Formation have been discussed in the most appropriate places throughout the foregoing account. The various environmental interpretations are combined in Fig. 4:9, to produce a palaeoenvironmental interpretation of the Stinchar Limestone Formation, a simplified palaeogeographic interpretation is shown in Fig. 4:10.

The recognition of a complex mosaic of shallow water carbonate depositional environments, in many ways comparable to present day

SCHEMATIC INTERPRETATION OF STINCHAR LST. FM. PALAEOENVIRONMENTS

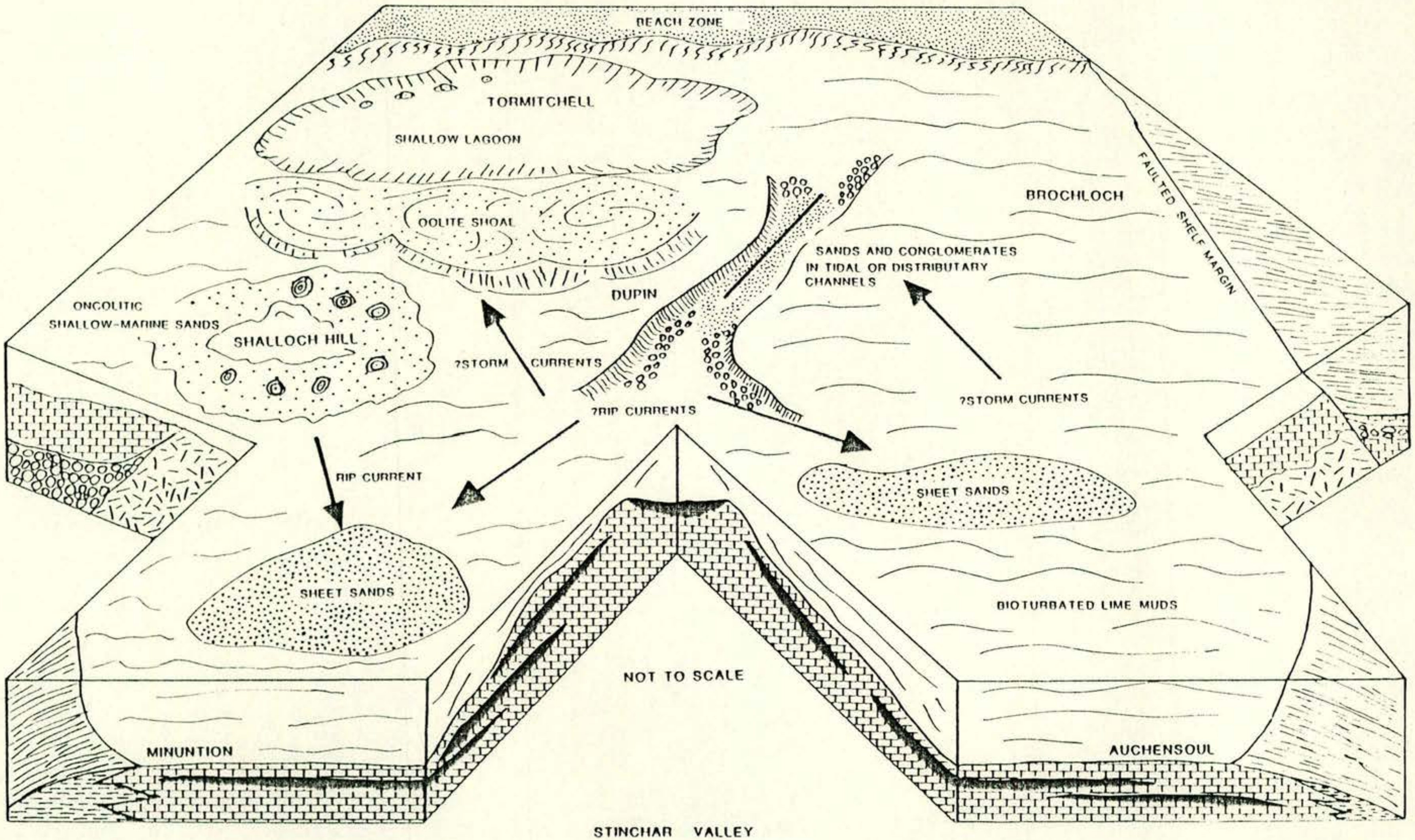
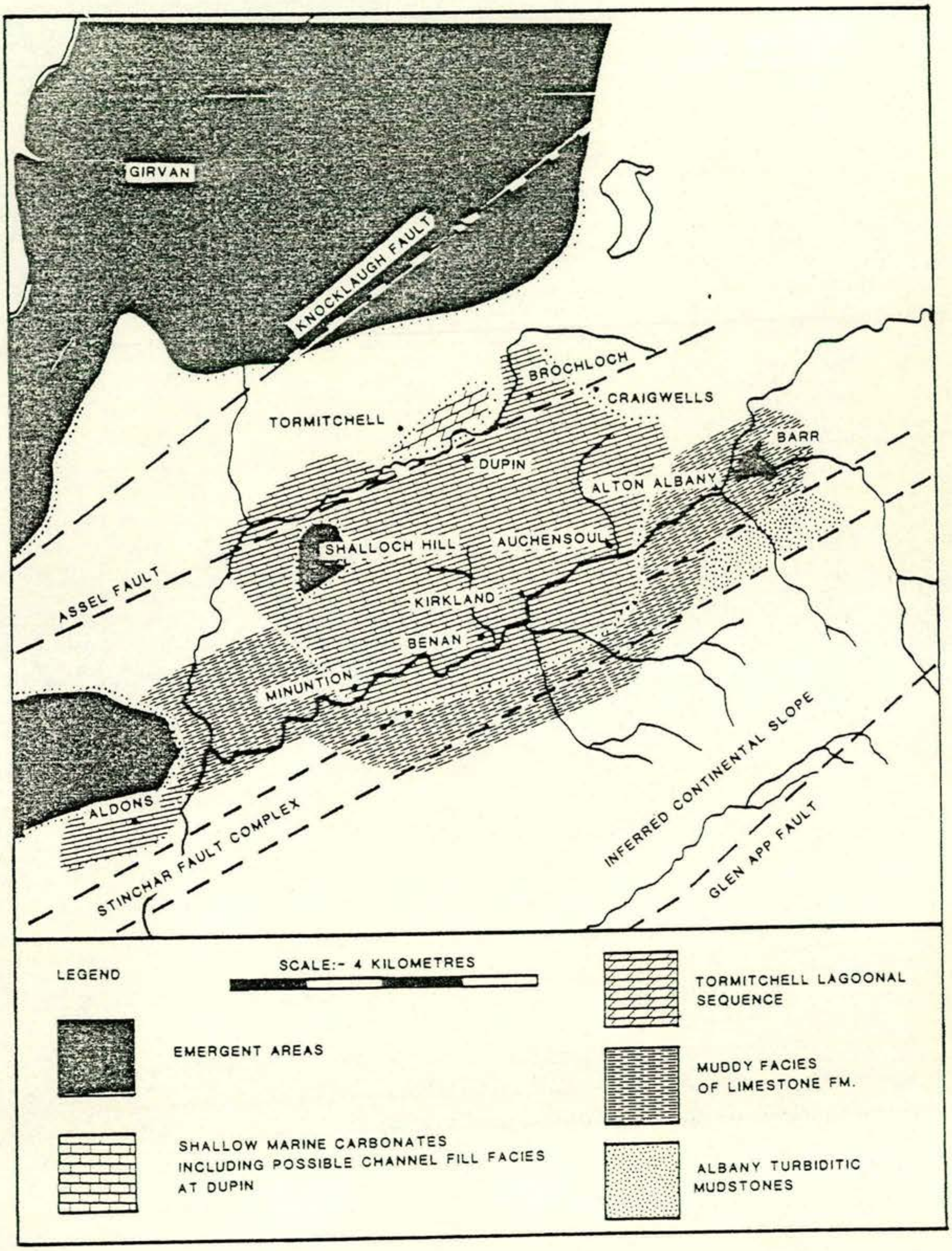


Figure 4.9

Simplified palaeogeography of the Stinchar Limestone Formation.



regimes, conclusively dispels the possibility, impled by Anderton et al. (1979, p.53) that the limestones may not have accumulated in an inshore setting.

The inferred overlap of the Stinchar Limestone Formation sediments onto a Ballantrae Complex basement that had not previously received any sediment, seen across the Water of Assel allows further comments as below.

(i) The Water of Assel may mark the location of a major fault, possibly the Assel fault of Williams (1962), that controlled sedimentation throughout deposition of the Kirkland Formation.

(ii) It is significant that no dramatic facies change takes place within the Stinchar Limestone Formation across the Water of Assel. This would suggest that the inferred fault, that was sufficiently major to allow the accumulation of at least 250m of Kirkland Formation sediment, may well have by this time ceased to be active.

CHAPTER 5

BENAN FORMATION

5.1 Introduction

As outlined in Chapter 2 the Benan Formation, consisting of a Lower Mudstone Member and an Upper Conglomerate Member, is the youngest of the three formations which together comprise the Barr Group. The Conglomerate Member, which forms the major part of the Formation, has not been studied in the same detail as the Kirkland Formation, due to lack of time to carry out what would be a large undertaking. For this reason study of the Benan Formation has been directed towards resolving a set group of problems, as listed below, that are considered important in gaining a fuller understanding of the Formation than before.

(1) The nature of the relationship between the Conglomerate Member and the Stinchar Limestone Formation which in places it is seen to overly with apparent erosional unconformity.

(2) The nature of the relationship between the Conglomerate Member and the Mudstone Member.

(3) Whether or not the Benan Formation truly represents a deep sea fan deposit, as suggested by Anderton et al. (1979) and Walton (1983), and whether transportation of detritus into the supposed deep water environment as a result of mass sliding in the manner proposed by Kuenan (1959), Williams (1962), and Ingham (1978), has really occurred.

The application of the facies concept to individual beds of gravel and associated clastic sediments has become an increasingly popular sedimentological tool in recent years. Such facies are defined on the basis of grain size composition, sedimentary structures and fossil content. This allows determination of the mechanisms involved in the deposition of a particular bedded unit. Within a sedimentary sequence, various associations of facies may be used to interpret the overall depositional environment. This technique is of particular use when interpreting a large amount of data, primarily measured sections, obviating the need for a lengthy analysis of numerous localities, and has been successfully applied to resedimented gravels by Davies and Walker (1975), Walker (1975), Surlyk (1978) and Nemec et al. (1980), and fluvial deposits by Rust (1978), Miall (1978) and Cant (1978).

This approach is not utilised here to its fullest extent as the amount of data available is small, and it is felt that a more 'stratigraphic' approach avoids confusions that might otherwise result. Comparisons of the various types of deposit present with established facies schemes are however made, to allow detailed interpretation.

5.2 Relationship of the Conglomerate Member to the Stinchar Limestone Formation

In the Barr Group type sections the Conglomerate Member is separated from the Stinchar Limestone Formation by the intervening Mudstone Member. 2.5km west of the type section, however, at exposures near the abandoned farmhouse at Auchlewan, the Conglomerate Member rests directly on limestones of the Stinchar Valley Member Pl. 5:1, Fig. 5:1. This relationship has in the past been the cause of much comment. Lapworth (1882) ascribed the juxtaposition of the two units to the effects of, "an important fault", combined with, "certain peculiarities in the basal beds of the conglomerate", evidently he did not accept that the entire thickness of the Mudstone Member could have been removed by any mechanism other than faulting. Henderson (1935) recognised this junction and another at Craigwells, section 4.3.2, as unconformities, and used this and other lines of evidence for the occurrence of submarine disturbances affecting sedimentation in the Girvan area during the Ordovician. Williams (1962) claimed that the base of the conglomerate, "delineates a remarkable diastem", 50m of mudstone in addition to an unknown thickness of limestone having been removed by erosion at the base of the conglomerate. This explanation was reiterated by Ingham (1978). Fig. 5:1 shows sections measured across the unconformity. These demonstrate clearly that the basal Conglomerate Member horizons initially infill a channel incised in the top of the limestone, but thereafter are no longer constrained by the channel margins. The basal units are pebble conglomerates and pebbly sandstones.

Plate 5.1

Figure 1.

Unconformable contact between planar bedded wackestones of the Stinchar Limestone Formation and gravelly sediment gravity flow/mass flow deposits of the overlying Benan Formation. The pebbly and cobbly gravels are clearly channelised, however as no material from the limestones is present as clasts it is not certain that erosion at the base of the conglomerates was neccesarily the agent responsible for the downcutting.

Outcrop above disused sheepfolds near Auchlewan farmhouse. (NX29,229 919)

Figure 2.

Contact between the Mudstone and Conglomerate Members of the Benan Formation. The two units are separated by a disturbed and admixed zone at the base of the overlying cobble and boulder conglomerates. The hammer lies on the disturbed zone.

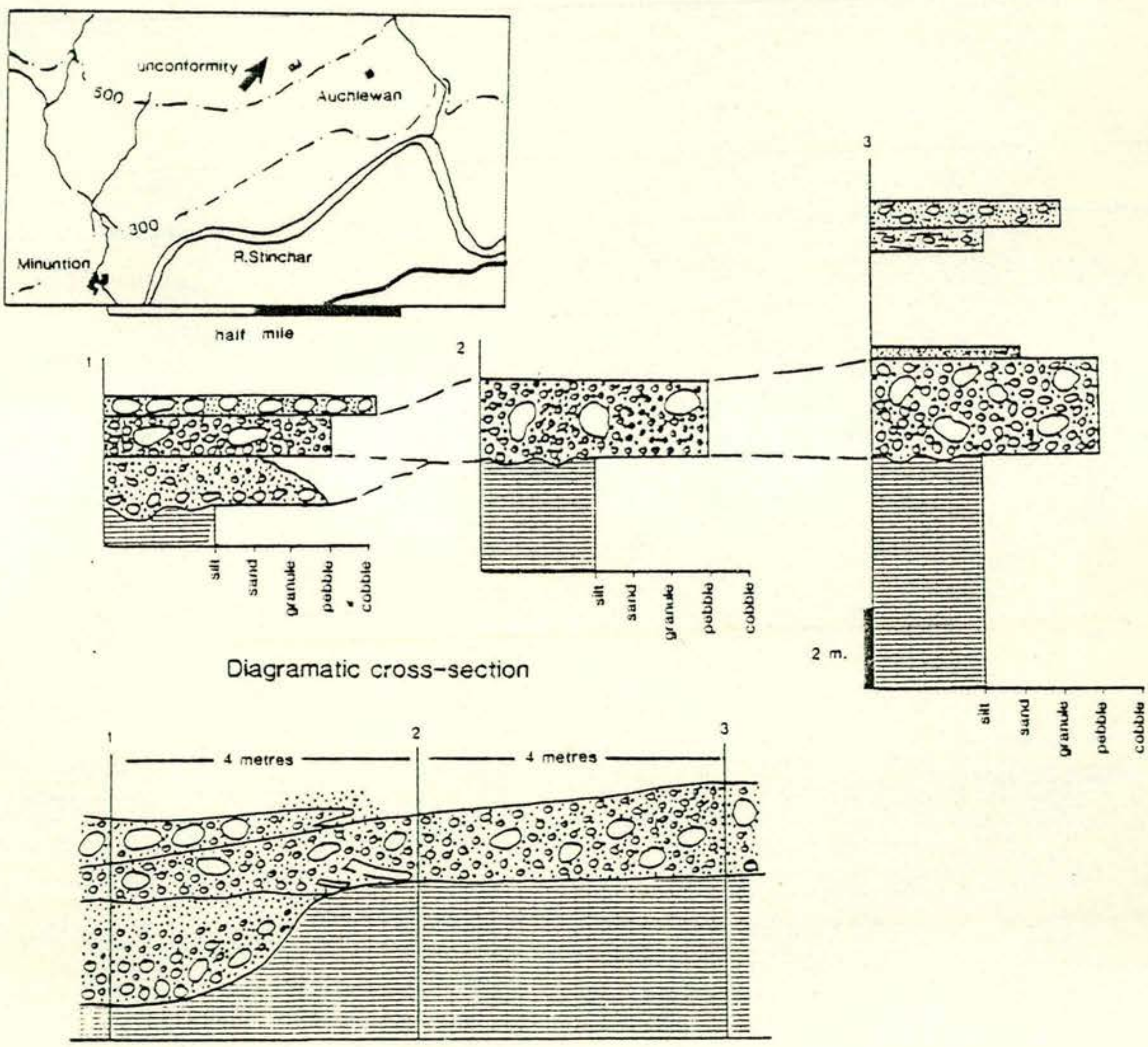
Crags above Benan Burn. (NX29,238 922)

Plate 5.1

Figure 1

Figure 2

MEASURED SECTIONS ACROSS UNCONFORMITY AT AUCHLEWAN



In places bedded units of limestone have been lifted away and intruded by sand as a result of compactional flowage of the conglomerate matrix. Whilst it is clear that a channel exists, cut into the limestone, it is not necessarily the result of erosion by the passage of currents laden with conglomeratic detritus. At exposures in the crags above Benan Burn, described in section 5.3, there is no sign of channelling into or major, large scale, removal of any part of the mudstone by the overlying conglomerate, instead a 0.5-1.0m thick disturbed zone is present, above a sequence in which the two units interdigitate (see section 5.3). With the exception of one horizon, below the base of the conglomrate, in Benan Crags, no exposures of rudites assigned to the Conglomerate Member contain rip-up clasts of material that could have been eroded from the Mudstone Member. In exposures where the basal units of the Conglomerate Member cut into the underlying Stinchar Limestone Formation abundant clasts of the carbonate unit are seen. Thus there is no firm evidence to indicate the removal of an extremely large volume of Mudstone Member sediment. The contact at the base of the Conglomerate Member may be attributable to erosion during deposition of the gravels, but could also be explained, albeit with an equal lack of conclusive evidence, by for instance emergence and erosion of the limestone in an intertidal zone. Prior to rapid submergence, the conglomerates thus infilling a pre-existing channel feature.

5.3 Relationship of the Conglomerate Member to the Mudstone Member

As outlined in the previous section earlier authors have maintained that the base of the Conglomerate Member is erosive into underlying deposits. Evidence has been put forward questioning this interpretation, however, for clarification of the issue, definite field evidence is needed. The junction between the Conglomerate and Mudstone Members is best developed in the crags overlooking Benan Burn (NX29 237 926). Examination of the existing exposures shows mudstones with sandy laminae overlain by pebble to boulder conglomerates, the two units being separated by a xone of disturbed, admixed sediment, Pl. 5:1, Fig. 2. Excavations made below the natural exposures demonstrate a more complex, intercalatory relationship between the two members. Sandstone beds clearly interdigitate with the mudstones, thinning and pinching out laterally, Fig. 5:2, moreover thin mudstones can also be seen to separate well defined conglomerate beds. This relationship is felt to indicate the gradual incursion of coarse grained detritus into an area formerly dominated by the deposition of mud and silt, rather than indicating a solely erosional contact at the base of the conglomerate. For these reasons the two units are considered to be laterally equivalent. Section 5.4 discusses the possible environmental significance of this relationship.

5.4 Mudstone Member

Outcrops of this member seen at various localities in the Stinchar Valley area display a number of minor variations. Conglomerates, siltstones and limestones, considered by Williams (1962) to be lateral equivalents of the Mudstone Member, outcrop along the Lendal Valley, but are not sufficiently well enough exposed to allow the collection of any worthwhile sedimentological data.

The main development of the member occurs in outcrops on the N. side of the Stinchar Valley, between Auchlewan and Auchensoul Burn, being absent from these sections. As seen at localities in Benan, Kirkland and Kirkdominae Burns the bulk of the member comprises laminated, non-fissile mudstones and siltstones, which as noted in the previous section, become coarser grained towards the top of the unit, sand laminae and well developed sandstone beds becoming increasingly important. The grading claimed by Williams (1962) to be present has not been observed in any of the material examined, rather, as recorded by Lapworth (1882, p.554, para.6) the mudstones are "distinctly laminated". Neither can the mudstones be correctly termed nodular, with the exception of the Aldons locality, any sphaeroidal form seen in loose material is the result of compactional/weathering phenomena, rather than a reflection of any primary feature of the sediment.

The base of the unit and its junction with the underlying limestones is not well displayed in natural exposures. Core recovered from I.G.S. Benan Burn does, however, show the passage excellently, Pl. 5:2 and Appendix II. The passage upwards from

Figure 5.2

MEASURED SECTIONS ACROSS MUDSTONE MBR.

CONGLOMERATE MBR. CONTACT, BENAN CRAGS

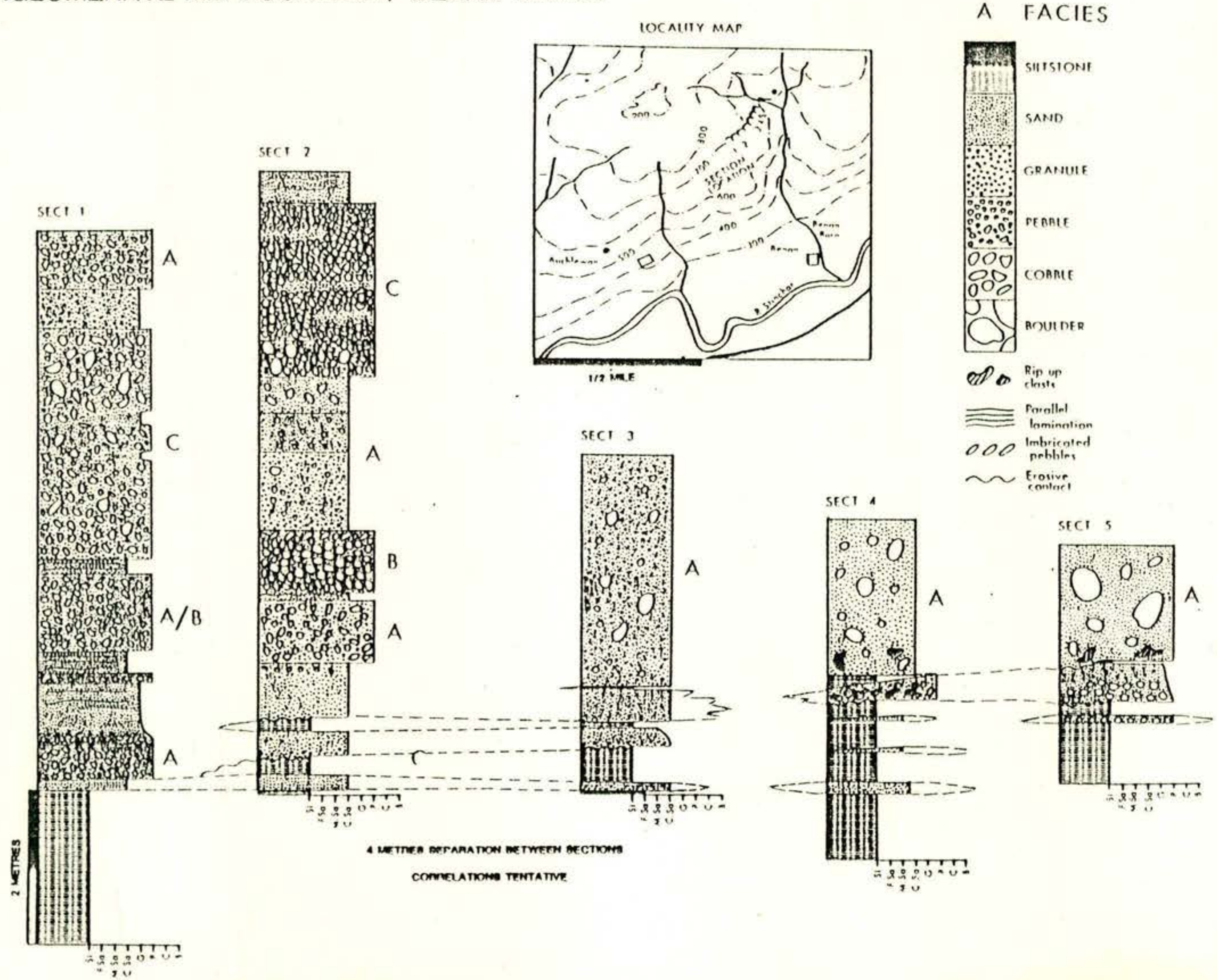
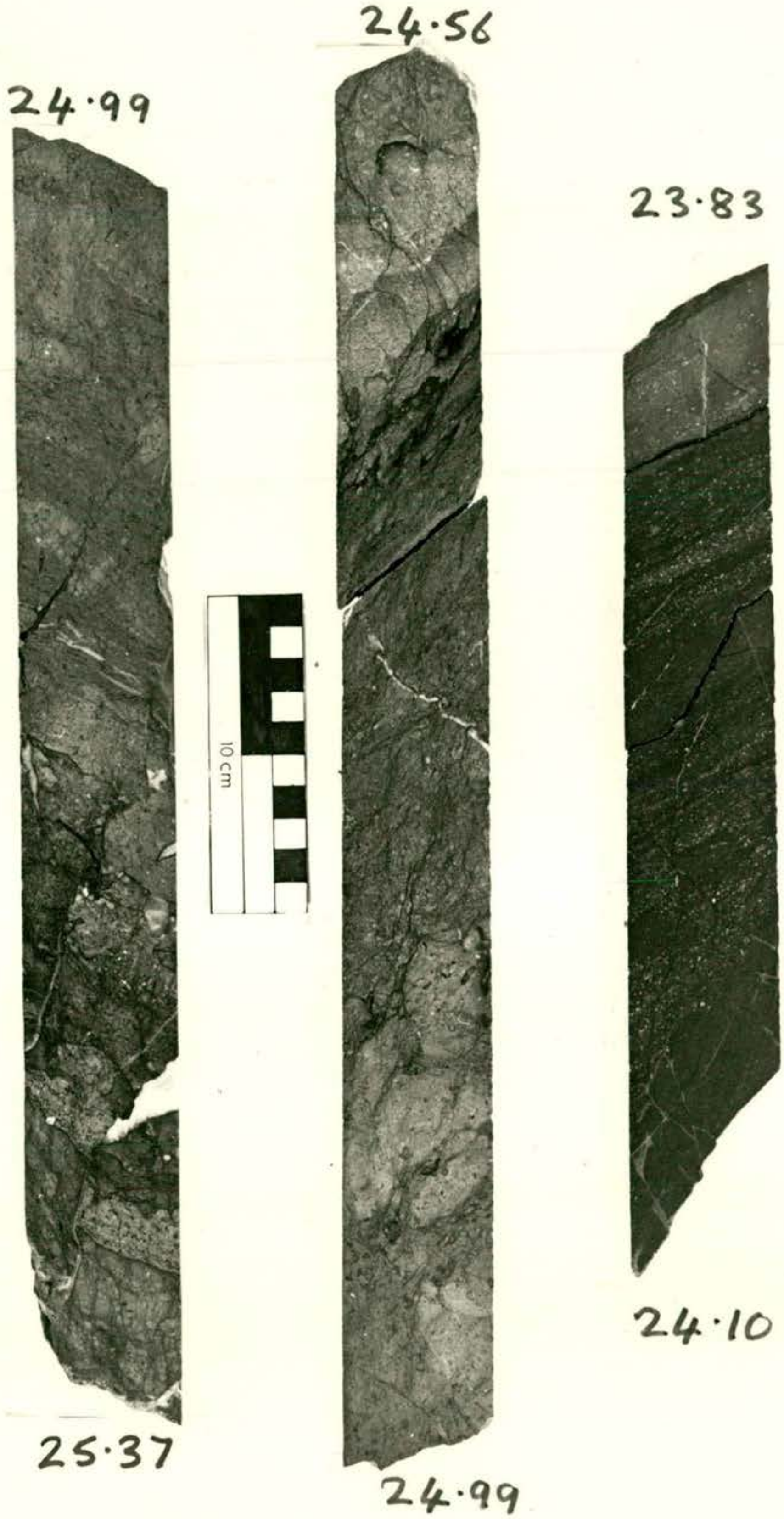


Plate 5.2

Core sections from the I.G.S. Benan Burn Borehole, showing passage from impure wackestones and grainstones at the top of the Stinchar Limestone Formation, into calcareous mudstones with laminae of crinoidal debris, these belonging to the Mudstone Member of the Benan Formation.


24·56
24·99
23·83
10 cm
24·10
25·37
24·99

the limestone member into the mudstones is remarkably rapid, being marked by a dramatic decrease in the carbonate component. Within less than 1m from the top of the limestone all trace of the biogenic carbonate is lost. When compared, for example, with the transition from the Benan Burn Sandstone Member into the Stinchar Limestone Formation the passage appears almost non-transitional.

Further west, along the Stinchar Valley, at Aldons Quarry, a thin development of mudstone is seen between the limestone and conglomerate. Here, however the mudstones contain calcareous concretions, these being composed almost entirely of skeletal carbonate, this type of material being absent from the surrounding muds. The nodules may therefore represent localised accumulations of bioclastic debris, possibly small winnow pockets, that cemented preferentially to the mudstones in the manner proposed by Henningsmoen (1974) for concretions in the upper Cambrian Alum Shales of Scandinavia.

The faunas recovered from the main Mudstone Member outcrops in the Benan area are limited, consisting of inarticulate brachiopods, Pl. 5:3, Fig. 2, bivalves, hyolithids (Pl. 5:3, Fig. 3) and graptolite fragments.

Bioturbation is almost absent, and only recognised by the occurrence of small scale burrows, Pl. 5:3, Fig. 1. The chondritiform burrows so abundant in the Limestone Formation are not seen at all in the Mudstone Member.

At the Aldons locality the fauna is far more prolific. Tripp (1976) records 64 species of trilobite, assigned to 47 genera, from weathered concretions. The most closely comparable fauna in the Girvan area is that of the Albany Mudstones (Tripp, 1965, Ross and Ingham, 1970) considered by Williams (1962) to be time equivalent to the upper part of the Stinchar Limestone Formation. The nature of the assemblage may indicate a broad similarity with the depth-related Nileid community of Fortey (1975), see section 4.7, thought to represent an offshore environment. Representatives of the shallower water Illaenid/Cheirurid community are also present, these however are considered to be allochthonous, having been transported downslope (Fortey, in Tripp, 1976). The fauna bears a strong resemblance to

Plate 5.3

Figure 1.

Small scale vertical burrow traces on the fractured, near bedding parallel, surface of core section. Such burrows provide the only evidence of bioturbation seen in the Mudstone Member.

Specimen no. BBH/X/280.

Figure 2.

Conjoined but distorted valves of an inarticulate brachipod, most probably a Lingulid.

Specimen no. BBH/X/380.

Figure 3.

Small bivalve from Benan Formation, Mudstone Member.

Specimen no. BBH/X/580.

Figure 4.

Cluster of densley packed hyolithids. The random orientation, disarticulation and occurrence in a more calcareous concretion may suggest that this is a faecal assemblage.

Specimen no. BB/1/80.

Plate 5.3

Figure 1
0.75cm

Figure 3

Figure 2
4mm

Figure 3
1cm

that occurring in the Lower Edinburg Formation of the Appalachian Valley, U.S.A. (Tripp, 1976) and of all the various faunas from the Girvan area shows the closest similarity to a North American assemblage.

Non-calcareous fossils recovered from unweathered concretions include acrotretacean brachiopods and conodonts as listed below:

1 pygodontiform element of Pygodus sp. most closely resembling P. serrus 4 falodontiform, and ostiodiform, elements of Peridon aculeatus.

The absence of primary sedimentary structures, such as rippling or grading in the mudstones recovered from the Benan Burn Borehole (Pl. 5:4) would seem to militate against deposition from fine grained turbidity currents. Surlyk (1978) interprets such fine grained, laminated but non-graded, sediments as having been deposited by settling out from suspension. Stow and Bowen (1980) propose a model for the deposition of non-graded muds from turbidity currents. The lamination seen in such sediments results from a separation of sand and silt fractions by shear sorting in the boundary layer at the base of a turbidite flow. Sediments deposited from turbidity currents may therefore be ungraded, and this mechanism cannot be ruled out as an agent in the deposition of the laminated mudstones, although deposition from suspension would seem more likely.

The upper parts of the Member exposed along the Stinchar Valley are made up of mudstones with interlaminated fine and medium sands. The coarser grained laminae are graded and are interpreted as having been deposited from turbidity currents. Surlyk (1978) describes closely similar sediments from the Jurassic of E. Greenland. As with the laminated mudstones, the interlaminated fine sand and mudstone occur as part of an association interpreted by Surlyk to represent the outer (distal) parts of a submarine fan complex.

5.5 Conglomerate Member

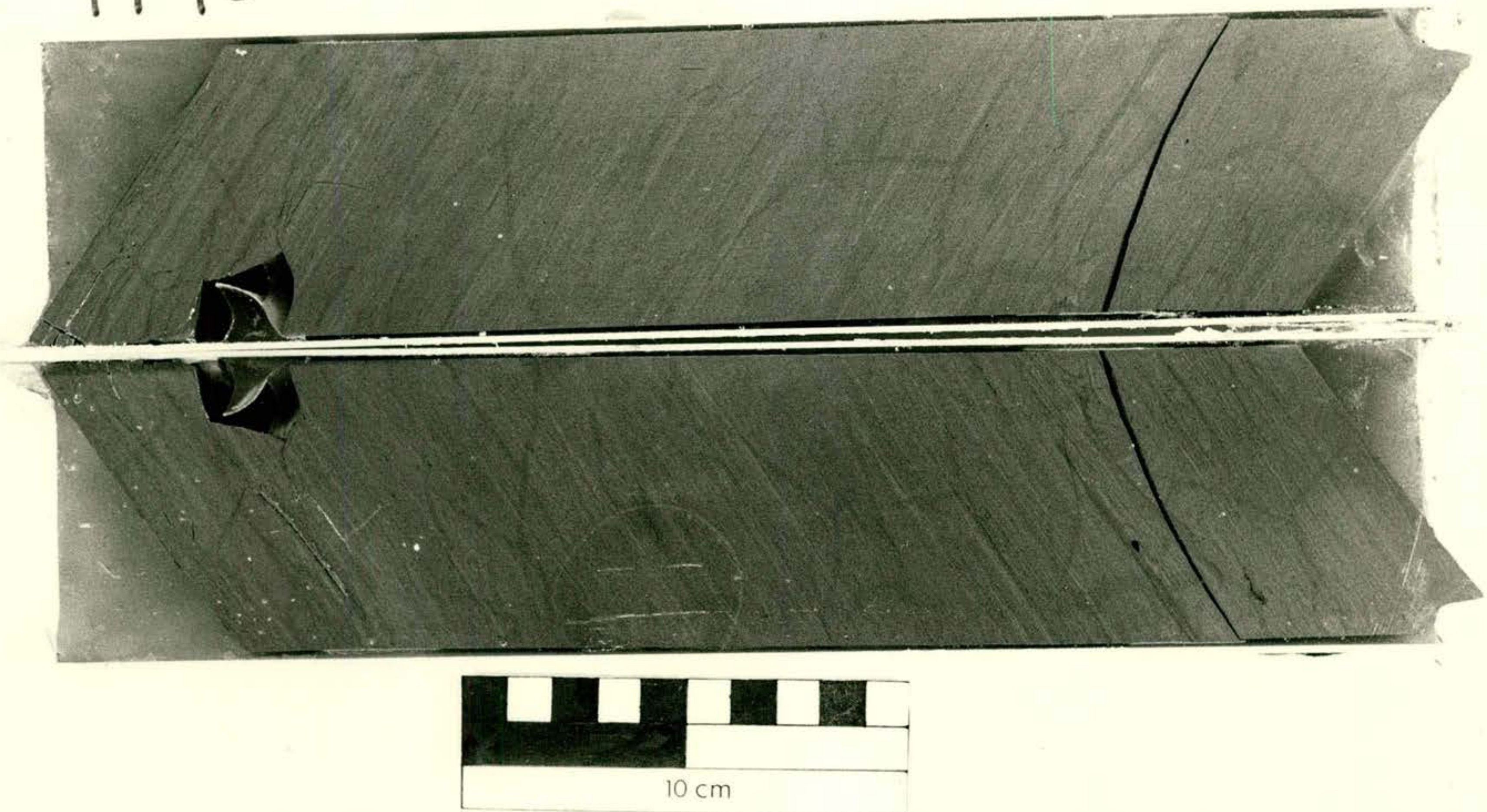
5.5.1 Introduction

Of all the established lithostratigraphic units in the Girvan sequence it is perhaps the Conglomerate Member (formerly Benan Conglomerate) that impresses itself most on the geologist in the field.

Plate 5.4

Core section, from I.G.S. Benan Burn Borehole, through the upper part of the Mudstone Member, showing fine, ungraded, horizontal laminae and absence of any obvious bioturbation.

17·18 17·45



The unit outcrops over a large area of the district, and as a result of the coarse, bouldery nature of certain horizons, is particularly distinctive. For the above reason Lapworth (1882) chose the conglomerate as a datum horizon, although Williams (1962) questioned the validity of this assumption.

The importance of the unit in assessing the validity of Williams accepted interpretation of the Girvan conglomerates as submarine slides has already been stated and will not be reiterated here. Instead, certain features of the Member will be described and their relevance to the accepted view discussed.

5.5.2 Lowermost horizons of the Member

Figs. 5:1 and 5:2 show sections through the lowest horizons of the Member, exposed along the Stinchar Valley. At this stratigraphic level the unit is composed predominantly of very crudely stratified pebble and cobble paraconglomerates, coarse sands and granule conglomerates (Fig. 5.2) with very rarely developed cross-stratification. Clast-supported, framework conglomerates are infrequently developed but when seen often possess thin but well defined sandstone intercalations (Fig. 5.2). Ungraded, well bedded, horizontally laminated sandstones occur not only in the measured sections, but also in the various isolated exposures around Benan and Auchensoul hills.

The well-developed reddening seen in the Kirkland Formation conglomerates and associated clastic sediments is not present in the Benan Formation; instead the matrix is greenish in colour. The clast population of the Conglomerate Member is notably different from the Kirkland Formation conglomerates; granite and reddened acid porphyries are distinctive and commonplace in the Benan Formation but are not seen in the Kirkland Formation.

Rb/Sr dating of the granite clasts has yielded isochrons at 470 m.y. and 560 m.y. (Longman et al. 1979). The younger age was obtained from coarse grained, pink granite clasts which are found throughout the member, as are clasts of a variety of carbonate lithologies, some of which are typical of the Stinchar Limestone Formation. The presence or absence of these two clast types provides the most reliable criterion by which the Benan Formation and Kirkland Formation conglomerates may be distinguished from each other. Sandstones in the unit are noticeably more quartzose than the dominantly lithic sandstones and conglomerate matrix of the Kirkland Formation clastics. Moderately well rounded grains of both polycrystalline and single crystal quartz comprise up to 50% of grains present, the remainder being the usual, locally-derived feldspathic and, to a lesser extent, lithic detritus.

The primary sedimentary features of conglomerates exposed at these low stratigraphic levels within the member cannot be interpreted using models proposed for gravels deposited in a coarse grained braided fluvial system, by Rust (1978) and Miall (1978). The clast imbrication and horizontal bedding typical of gravels deposited on longitudinal bars and cross-stratification typical of inter-bar sounds are not seen in these conglomerates. Neither are the models proposed for re-sedimented conglomerates, by Davies and Walker (1974), Walker (1975) and Walker (1978), applicable, as the grading, whether normal or inverse to normal, and clast imbrication described by these authors are not seen. Walker's models were, however, developed from a study of conglomerates deposited in a deep water, submarine fan setting, along with associated turbidite sands. The lower horizons of the Conglomerate Member were, along with the Mudstone Member, most probably deposited at outer shelf water depths, and models for deep sea deposits may apply.

Closely similar conglomerates have, however, been reported from Jurassic sediments of the Wollaston Foreland, E. Greenland, by Surlyk (1978). Surlyk interprets these gravels as having been deposited on submarine fans formed in indeterminate water depths, these fans accumulating distally to fan-deltas, in basins created by rotational subsidence of major fault blocks during an early phase of North Sea rifting.

The facies scheme utilised by Surlyk (1978) can be applied to the Benan Formation conglomerates as shown below:

Table 5.1

	Benan Facies	Surlyk sub Facies	Interpreted depositional mechanism
A	**Non-graded matrix supported disorganised**	8a	Absence of an organised fabric and grading suggests that the matrix had enough strength to support the clasts and that the facies was deposited by freezing of subaqueous debris flows. Matrix strength alone was probably not the only supporting mechanism. Density differences between the clasts and matrix is slight, thus increasing buoyancy of clasts. The facies is interpreted as having been deposited from sandy debris flows transitional to density-modified grain flows.
B	Clast supported non-graded disorganised	8h	Dispersive pressure caused by clast interaction was probably the main supporting mechanism, aided by matrix strength and buoyancy. Deposition occurred from density modified grain flows transitional to sandy debris flows.
C	Composite conglomerates	8G	Deposited from sediment gravity flows where matrix strength and clast interactions dispersive pressure were the dominant support factors. (see text also)

Resedimented conglomerates of the Ksiaz Formation (L. Carboniferous, S.W. Poland) interpreted as fan delta slope deposits (Nemec et al. 1980) show a facies spectrum similar to that described by Surlyk, and were similarly thought to have been deposited from modified debris flows.

Although debris flows are usually typified by a fine grained often muddy matrix, and matrix supported fabrics, the lack of these features does not preclude deposition by this mechanism (Middleton and Hampton, 1976).

The inverse grading developed in unmodified grain flow deposits, either as a result of dispersive pressure (Bagnold, 1954, 1968) or a kinetic sieve effect (Middleton, 1970) is not, however, seen in either the Greenland, Ksiaz Formation or Benan Formation conglomerates. Composite conglomerates of Facies C, are interpreted by Surlyk as the end result of progressive failure on a slope. This results, in a series of retrogressive flows, resedimenting earlier conglomerates and sandstones in-masse, in the manner proposed by Hendry (1973) for similar conglomerates in the Lower Ordovician of Quebec.

The ungraded sandstones that occur interbedded with the conglomerates are either structureless or faintly parallel-laminated, deposition may have taken place from any one, or combination of, mass flow mechanisms.

The mechanisms by which these gravels were deposited is therefore fairly clear; more problematic, however, is the identification of a definite depositional sedimentary environment. Certainly, whatever the environment in which the gravel accumulated prior to resedimentation it must have been a major site of coarse clastic deposition, and it is considered that a fan delta or coastal alluvial fan are the only settings from which such a large volume of coarse grained sediment could have been derived.

Whilst it is probably that the eventual site of sediment accumulation was relatively downslope it is not certain that the detritus was deposited in the form of a submarine fan, sensu Walker (1978), although more field work would be necessary to finally resolve this question.

5.5.3 Limestone horizons in the Conglomerate Member

(i) In-situ carbonates

The only exposures of these limestones currently available occurs in the bed of a small stream that flows S.E. off the Fell of Pingerrach (NX29 270 943). The horizon in question consists of two limestone beds separated by a 25cm thick unit of pebble conglomerate, Pl. 5:5, Fig. 1. The lower of the two limestone horizons is a 30cm thick, strongly reddened algal carbonate containing only fine grained terrigenous detritus. Girvanella is the only identifiable alga present, displaying a similar variety of growth forms; viz, laminar, upright digitate and flocculose mat, as seen in the Auchensoul Limestone Member.

The upper unit comprises 20cm of somewhat less reddened limestone with isolated pebbles occurring throughout, Pl. 5:5, Fig. 2. The internal organisation of this horizon is rather more complex than that of the lower unit consisting of densely packed, sinuous, tubes of the foraminiferid Wetheredella, Pl. 5:6, Fig. 1, wrapping round and encrusting pebbles of the underlying conglomerate, Pl. 5:5, Fig. 3, occupy the Lower 3-4cm of the horizon passing upwards into algal limestone composed almost wholly of Girvanella, Pl.5:6, Fig. 2, this forming the great part of the unit, Pl.5:5, Fig.2. Although Riding (1975) argues against using the presence of algae, and in particular Girvanella, to indicate rigidly constrained water depths, it is clear that algal growth will occur most vigorously in shallow, clear, water. The present author is not aware of any instance, recorded in the literature, where abundant algal growth occurred other than in a shallow marine, intertidal or supratidal environment.

(ii) Carbonate clasts

In addition to the in situ carbonates, numerous clasts of reddened algal/coral limestones clearly different from those derived from the Stinchar Limestone Formation are seen in low horizons of the Conglomerate Member, these being particularly abundant in Auchensoul Burn. Of the clasts collected from this locality, the most interesting is that shown in Pl.5:6, Fig.3. The specimen is a boulder of patchily reddened coral/algal limestone, with clastic material adhering to the outer surface. Three large coral colonies are seen, Pl.5:6, Fig.3, the fasciculate tabulate Eofletcheria

Plate 5.5

Figure 1.

Two thin algal limestone horizons (arrowed) in the Conglomerate Member, separated by a thin band of pebble conglomerate. The specimen shown in the next four figures was removed from above the hammer handle. Outcrop in stream bed Fell of Pingerrach. (NX29,268 942)

Figure 2.

Cut surface showing clearly defined foraminiferal and algal portions of the horizon.
Specimen no. FP/1/81.

Figure 3.

Photomicrograph showing encrustation of gabbroic pebble by a foraminiferid, probably Wetheredella.
Thin section, FP/1/81, plane polarised light.

Plate 5.5

Figure 1

Figure 2

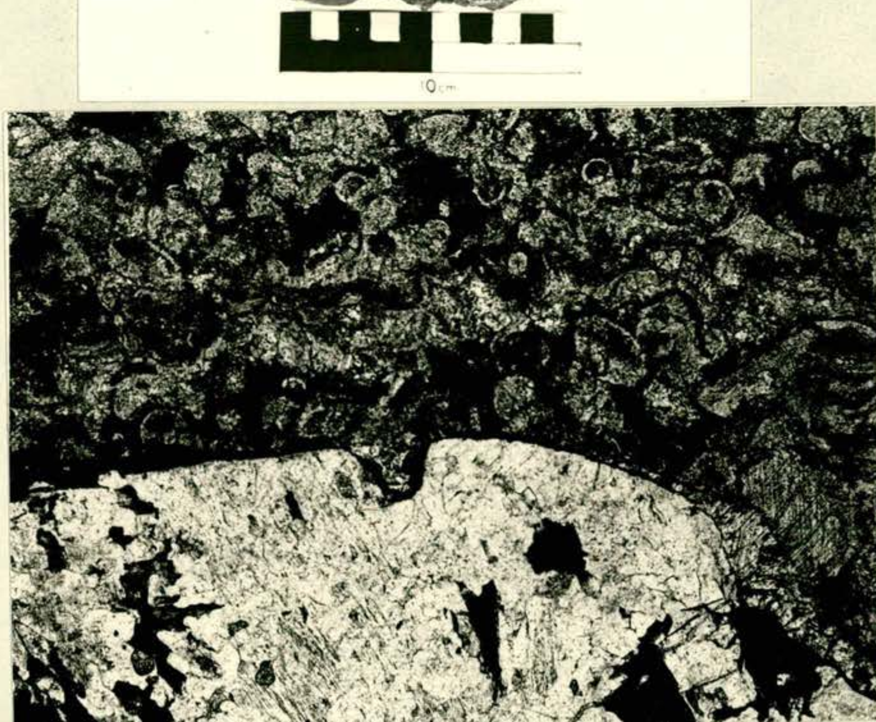


Figure 3
0.25mm

irregularis, and a tabulate coral assigned to the genus Lyopora both being present. Areas between the coral colonies are infilled by calcite cemented, coarse lithic/quartzo-feldspathic sand, Pl.5:7, Fig.1. Corallites of Eofletcheria irregularis are frequently encrusted by Girvanella, which in places may completely infill the intercorallite areas, Pl.5:5, Fig. 1. The problematic alga Izhella (Pl. 5:8, Fig. 2) also occurs within the coral-algal framework, intergrown with the Girvanella filaments. A thick 5-7cm, layer of tightly intertwined Girvanella occurs draped over the upper surface of the coral framework. Pl. 5:6, Fig. 3.

The Girvanella, growths are dominantly laminar, allowing the development of shelter cavities, Pl. 5:7, Fig. 2. The internal structure of the algal growths is also essentially horizontal, the filaments extending laterally and entwining tightly around each other to give a cables appearance, Pl. 5:7, Fig. 3. The organisation of these and other Girvanella filaments described in Chapter 4 is very closely comparable with that described by Golubic (1973, fig.21.11, p.455) from present day Scytonema mats occurring in intertidal and supratidal zones of the Bahamas and Shark Bay, Australia. Similar mats may form in sheltered and nutrient rich subtidal environments, freely moving species of the genera Oscillatoria and Spirulina are the dominant components of such mats, (Golubic, 1973, p.448 and references therein). The similarity of the Girvanella problematica growths to these present-day motile algae may strenghten the argument of Lauritzen and Worsley (1974) and Riding (1975), that at least certain members of the genus Girvanella may be allied to the Oscillatoriaceae. At the same time the contrast between this growth form and others recorded in this thesis further highlights the problems inherent in assigning Girvanella as an entire genus to any one of the various cyanophyte familites that bear a gross morphologic similarity to these fossil remains.

In areas between the filament bundles neomorphism of both the micritic matrix and the algal filaments has occurred, Pl. 5:7, Fig. 3.

The roofs of primary, shelter, cavities in what is essentially a small scale framework, may be colonised by non-filamentous, coccoid, algae, Pl. 5.8 Fig. 1 , comparable to the problematic genus Epiphyton,

Plate 5.6

Figure 1.

Densely packed Wetheredella tubules intergrown with Girvanella filaments.
Thin section, FP/1/81, plane polarised light.

Figure 2.

Area of algal filaments in foraminiferid/algal stromatolite.
Thin section, FP/1/81, plane polarised light.

Figure 3.

Cut surface of loose block, collected from Auchensoul Burn. The specimen is composed largely of corals, including the branching form Eofletcheria irregularis, intergrown with Girvanella which in the upper part of the specimen totally overgrows the corals. Intercorallite areas are infilled with a sand matrix.
Specimen no. AUB/7/80.

Plate 5.6

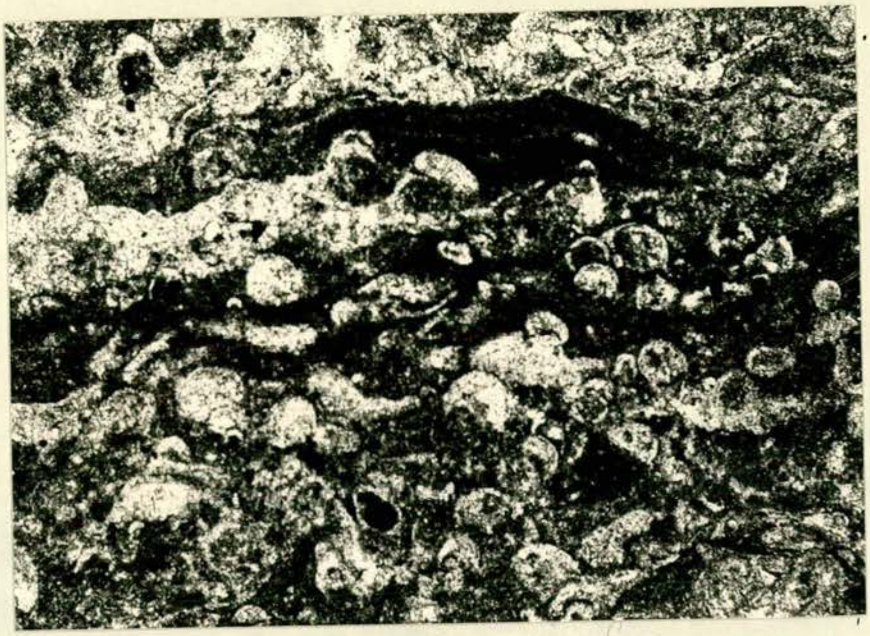


Figure 1

0.2mm

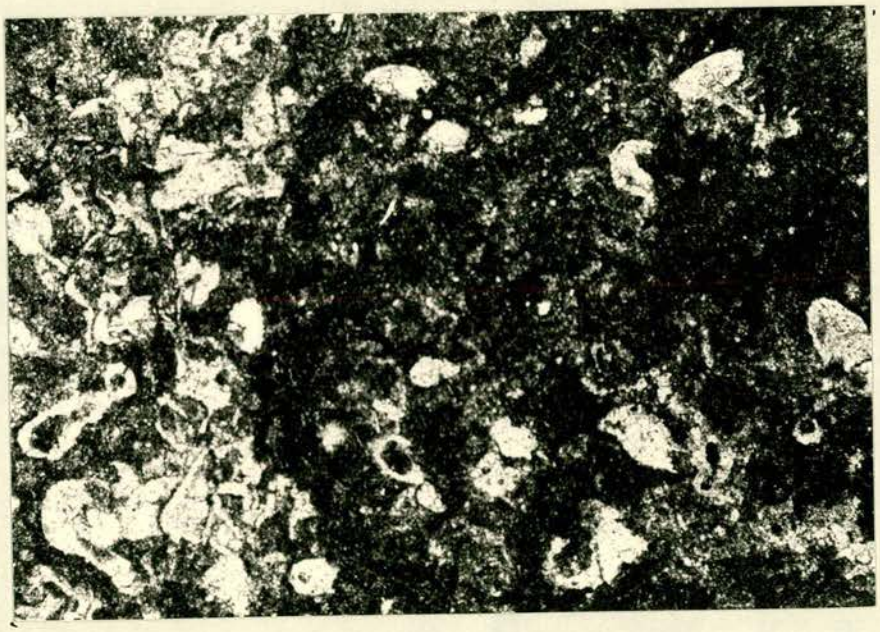


Figure 2

0.2mm

Figure 3

Plate 5.7

Figure 1.

Corallites of Eofletcheria irregularis intergrown with and encrusted by Girvanella (G).
Thin section, AUB/7/80B, plane polarised light.

Figures 2 and 3.

Detail of Girvanella filaments forming a stromatolitic cap to the coral growths. The algal filaments wrap around each other, forming 'cabling' bundles that may develop in either vertical or horizontal planes.
Thin section, AUB/7/80, plane polarised light.

Plate 5.7

Figure 1

4mm

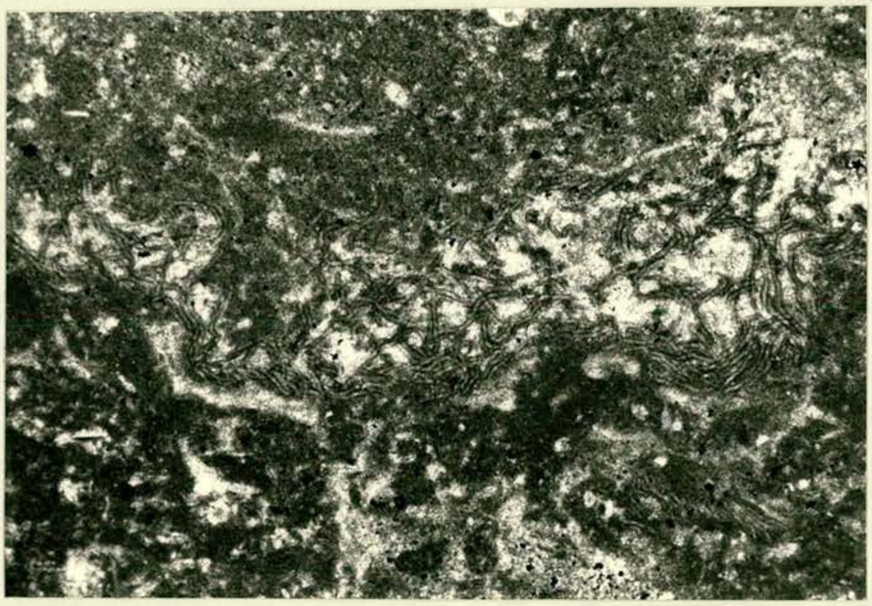


Figure 2

0.4mm

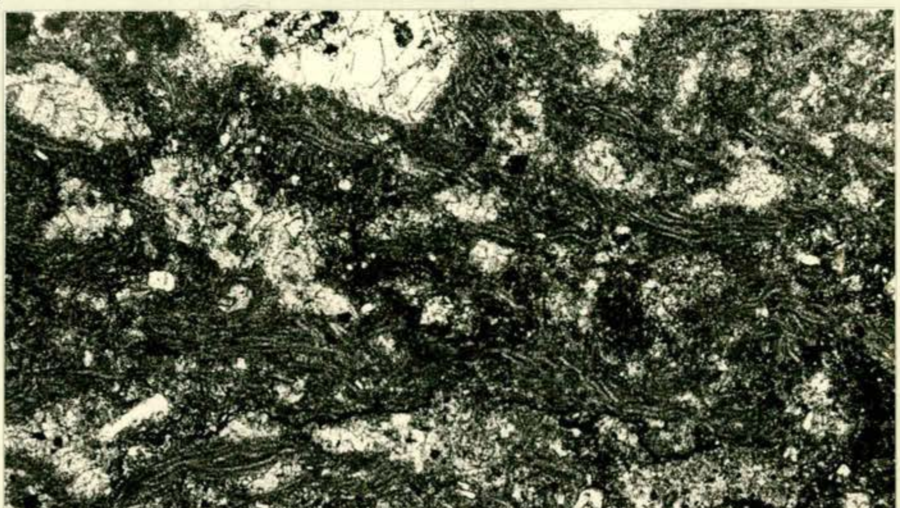


Figure 3

0.35mm

Plate 5.8

Figure 1.

The problematic alga Epiphyton (E) encrusting corallites of Eoflectcheria irregularis.

Thin section, AUB/7/80, plane polarised light.

Figure 2.

Poorly preserved growths of the problematic alga Izhella, within coral/algal limestone boulder.

Thin section, AUB/7/80, plane polarised light.

Figure 3.

Horizontally stratified conglomerates and massive, matrix supported, conglomerates outcropping in bed of Water of Gregg. (NX29,9405 2785)

Plate 5.8

Figure 1

4mm

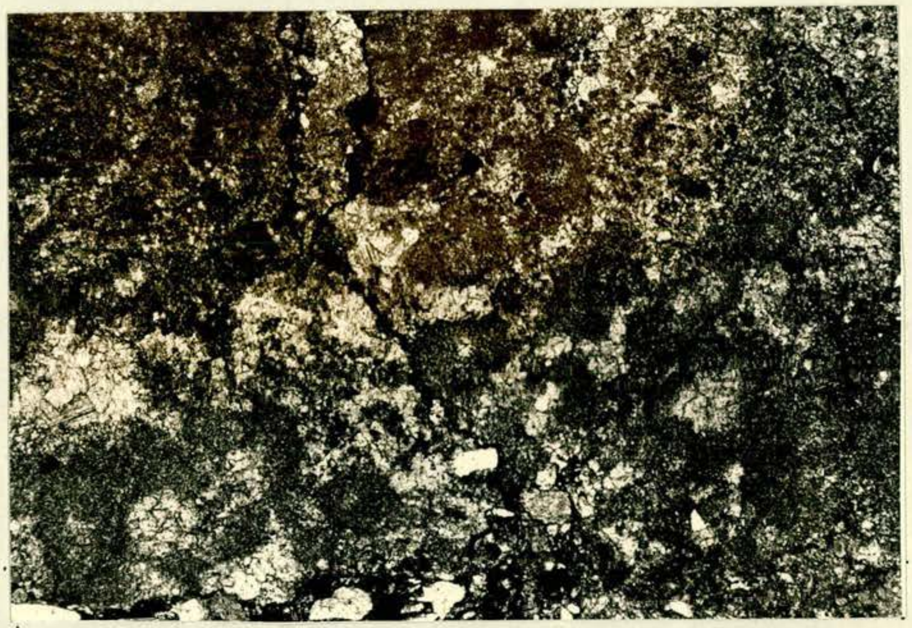


Figure 2

0.4mm

Figure 3

either the remains of a coccoid cyanophte (Riding, 1981, pers.comm.) or a red alga (Korde, 1959). The cavities are geopetally partially infilled by fine grained detrital material, the remaining porosity being occupied by moderately coarse, 'bladed', non-ferroan calcite,

The overall structure of the block is reminiscent of a small patch or button 'reef'. As with the in-situ limestone bands, boulders such as these are interpreted as shallow water deposits, whether or not they were later transported into a different environment.

5.5.4 Horizontally stratified units of the Conglomerate Member

Whilst the gravels occurring at low levels of the Conglomerate Member are generally poorly stratified, higher horizons, particularly those outcropping in the beds of the R. Stinchar and the Water of Gregg around the village of Barr are horizontally stratified. Of these, those in the Water of Gregg are the best exposed, outcropping immediately above the bridge to Dinmurchie Farm (NX29 2790 9405), Pl. 5:8, Fig. 3 shows the larger part of the available outcrop in which three conglomerate facies can be distinguished. Matrix-supported, pebble and cobble conglomerates occur at the base of the section and are overlain by 3-4 metres of horizontally-stratified pebble conglomerate with interbedded granule-rich sandstones. Above this unit the gravel component decreases in importance, sandstones being better developed than at lower horizons.

The basal matrix-supported conglomerates are poorly stratified and lack any discernible sedimentary structure that might indicate a particular depositional mechanism or environment. The two upper units are, however, more informative. The well stratified conglomerates with interbedded horizontally laminated sands are the most diagnostic. Pebble conglomerates occur as laterally continuous (over 5-10 metres, the extent of the available outcrop), Pl.5:9, Fig.1, generally sharp based, horizontally stratified, variably imbricate units, Pl. 5:9, Fig. 2, that are generally normally graded, although inverse grading may also occur, Pl. 5:9, Fig. 3.

The style of imbrication, whether clast long axes are parallel with or normal to the imbrication direction, is impossible to

Plate 5.9

Figure 1.
Horizontally stratified dominantly clast supported, imbricate conglomerates in Benan Formation outcrops in the Water of Gregg.
(NX29, 9405 2785)

Figure 2.
Detail of horizontally stratified conglomerates, showing very well developed imbrication, currents flowing from bottom to top -roughly N - S in outcrop.
Locality, Water of Gregg, NX29,9405 2785.

Figure 3.
Inversely graded horizontally bedded gravels. The inverse grading may reflect winnowing of a bar top.
Locality, Water of Gregg, below Dinmurchie Bridge, NX29,940 278.

Plate 5.9

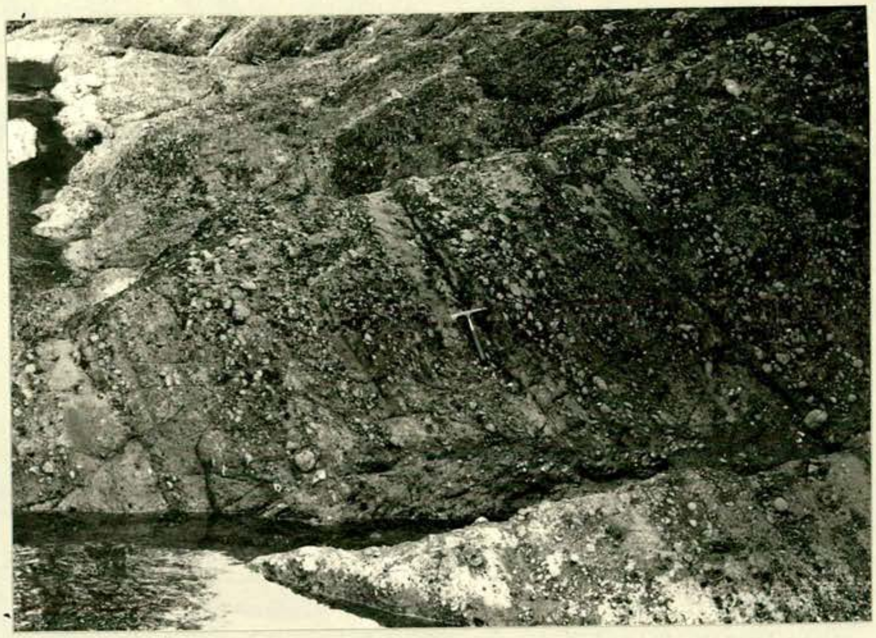


Figure 1

Figure 2

Figure 3

determine as the sediment is well-cemented, thus no distinction between a fluviatile or resedimented fabric is possible on the basis of imbrication. The imbrication does, however, record palaeocurrent, which in this case would appear to be variable, flowing from directions between northeast and northwest. The imbrication clasts are generally tabular but not discoidal and are rather poorly rounded, Pl. 5:9, Fig. 2. The uppermost conglomerate facies is less clearly stratified than the former. Instead, the gravels are, in most cases, paraconglomerates and bedding is less well developed than in the stratified facies. The sandstone units are coarser than at lower horizons and show large-scale, trough-cross stratification, forsets being marked by granule-rich laminae these again indicating generally N.-S. flowing palaeocurrents. In no instance was any form of normal, or inverse to normal grading seen in these exposures. Resedimentation by any mass-flow mechanism would therefore seem improbable, since none of the criteria proposed by Davies and Walker (1974), Walker (1975) and Walker (1978), for the recognition of such deposits are fulfilled. Similarly, conglomerate facies of the types recorded by Surlyk (1978) and Nemec et al. (1980), also from resedimented deposits, are not seen.

Such features are, however well known from coarse grained braided fluvial systems and may be described using the facies code erected for such deposits by Miall (1977). Each of the facies types recognised by Miall has a broad genetic significance as below, Table 5:2.

TABLE 5:2

Miall. Facies	Lithofacies	Sedimentary Structures	Interpretation
GMs	massive matrix supported gravel	none	debris flow sieve deposit channel lag deposits
Gm	massive, or crudely bedded gravel clast supported	horizontal bedding imbrication	deposition on longitudinal bars, formed by unconfined flow at flood stage
st	sand, medium to very coarse may be pebbly	solitary(theta) or grouped(pi) trough crossbeds	Lower flow regime dunes or migrating mega-ripples within channel
Sh	sand, very fine to very coarse, may be pebbly	horizontal laminations panting or streaming lineations	planar bed flow (lower and upper flow regime) within channel

A sieve deposit origin for the stratified gravels is thought to be unlikely, these usually being developed in the most proximal, fanhead, areas of alluvial fans, where they are normally rather coarser grained than the Water of Gregg conglomerates and lack horizontal stratification (for description see Bull, 1972). Thus these Benan Formation gravels most probably reflect a braided fluvial environment, deposition occurring on longitudinal bars,inversely graded units may represent winnowing of the bar top during waning flow stage. The cross-stratified sandstones probably accumulated at low flow stages as dunes migrating within a between-bar channel. Massive structureless paraconglomerates, are thought to have been deposited from sandy debris flows. The association of these two facies types is reported by Williams and Rust (1969), from the Donjek River, Yukon, Canada, used to produce models for proximal braided fluvial deposits by Rust (1972, 1975, 1978, 1979) and Miall (1977, 1978). Similarly these two facies are the dominant deposits in proximal paraglacial gravels from Iceland, proposed as a model for humid alluvial fan deposits (Boothroyd and Ashley, 1973, Boothroyd and Nummedal, 1978) and also in Tertiary alluvial fan and fan-delta deposits in S.W. Turkey, described by Hayward (1982).

The well developed stratification seen in the Benan Formation conglomerates is related to the gravel:sand ratio, as suggested by Williams and Rust (1969). The observed variation in dip direction of imbricated clasts is not inconsistent with deposition in a braided fluvial system. An alternative interpretation of the horizontally stratified conglomerates might perhaps be made on the basis of the segregation of the sand and gravel fractions into relatively well defined, laterally extensive units. Clifton (1973) suggested that bed lenticularity and poor segregation of pebble sand fractions typify alluvial gravels. Wave worked gravels, however, may be characterised by a higher degree of pebble/sand segregation and more laterally extensive, less lenticular gravel beds. As proposed these criteria may provide a useful method by which fluvial and shallow marine environments may be visually distinguished. It might, therefore be argued that the Water of Gregg conglomerates represent shallow marine/intertidal deposits.

Several features of these gravels are, however, thought to be inconsistent with a wave reworking hypothesis. Firstly the lack of any significant rounding to discoidal forms of the relatively susceptible basalt clasts does not indicate a prolonged period of abrasion and attrition in the intertidal zone. Palaeocurrent directions as indicated by pebble imbrication and rare cross-bedding show currents flowing from N.-S., the same general regime as is seen in the Kirkland Formation. Were beach, intertidal or shallow subtidal processes active, it is probable that the imbrication would have a markedly different orientation, reflecting shoreline slope and facing direction rather than palaeocurrent. Given the relatively small scale of outcrop the apparent lateral persistence of gravel units has little significance, as longitudinal bars of this size are common. Thus the caution advocated by Clifton (1973) is probably well applied in this case, and as Clifton notes, terrestrial mechanisms such as those operating in braided streams or on alluvial fans, "may produce evently persistent, well segregated pebble beds".

5.5.5 Southernmost correlatives of the Conglomerate Member

Approximately 1.3km upstream from the previous locality the most southerly correlatives of the Conglomerate Member outcrop in a small gorge cut by the Water of Gregg (NX29 291 939). The sequence consists of parallel laminated or rippled fine sands and interbedded laminated siltstones. These coarsen and thicken upwards into well developed coarse sands, Fig. 5:3. The sands are rapidly replaced by channelised conglomerate (Pl. 5:10, Fig. 1) and granule rich very coarse sands. Most of the coarse grained beds have erosive bases, some of which are loaded, Pl. 5:10, Fig. 2, indicating relatively rapid deposition. The thick, granule-rich very coarse sands may be multiply-graded (Pl. 5:10, Fig. 1), and are thus amalgamated beds. Correlation with the Benan Formation is on the basis of the occurrence of clasts of lithologies typical of the Stinchar Limestone Formation itself and also as clasts in the Conglomerate Member of the Benan Formation. The exact stratigraphic level of this sequence is however not determinable, due to the absence of any faunas both in these exposures and the Conglomerate Member itself.

Plate 5.10

Figure 1.

Thick resedimented gravels, containing clasts of Stinchar Limestone Formation (e.g. to right of hammer head) and associated graded, turbiditic, sandstones in 'distal' areas of Benan Formation outcrop. Locality, Water of Gregg, near The Stables, NX29,939 291. Scale is given by hammer (30cm).

Figure 2.

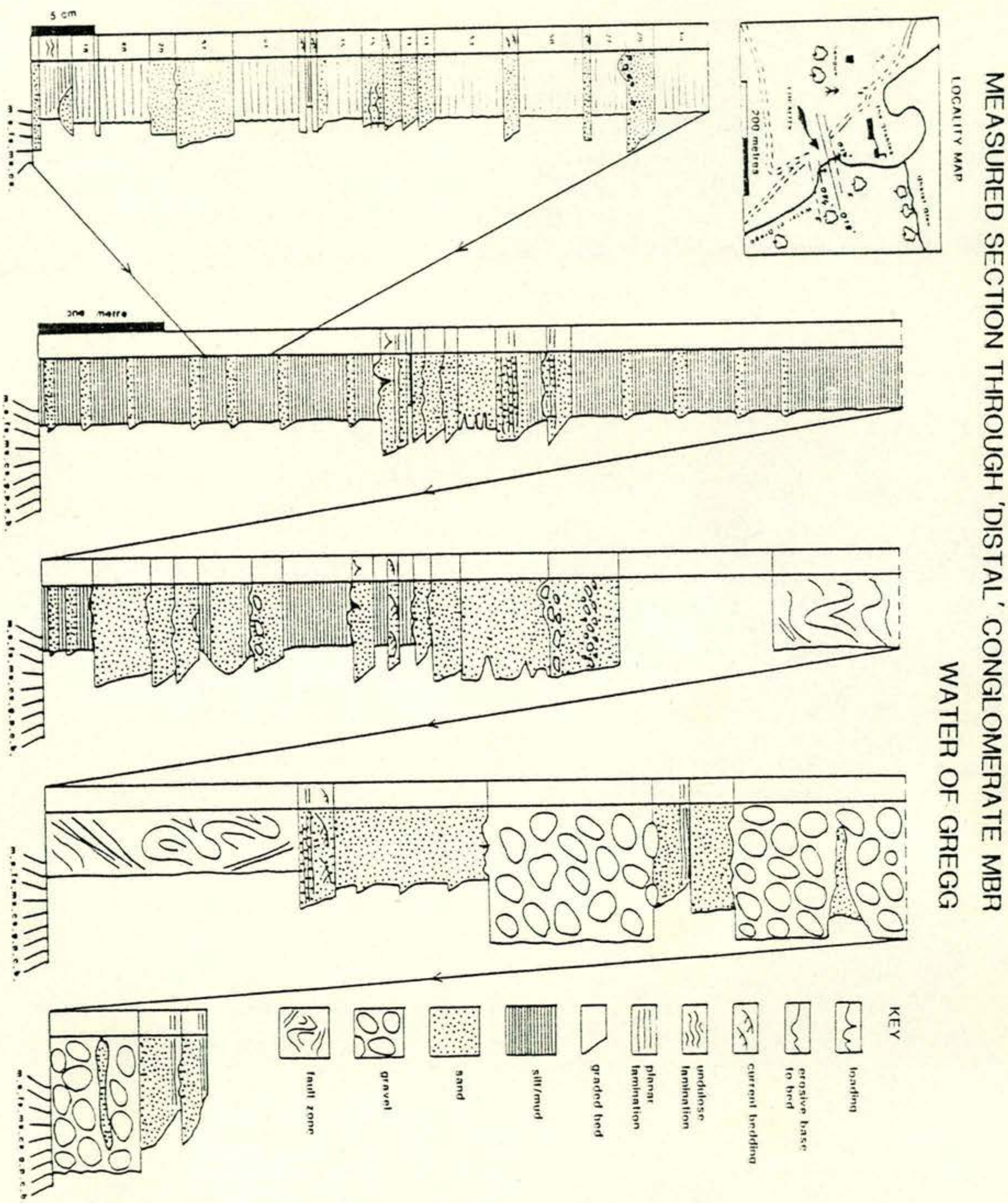
Graded, turbiditic, sandstones and granule conglomerates in 'distal' areas of Benan Formation outcrop. The beds young from right to left. Locality, Water of Gregg, near The Stables, NX29,939 291. Scale is given by hammer (30cm).

Plate 5.10

Figure 1

Figure 2

Figure 5.3


MEASURED SECTION THROUGH 'DISTAL' CONGLOMERATE MBR
WATER OF GREGG
LOCALITY MAP
200 metres
5 cm
one metre
KEY
loading
erosive base to bed
current bedding
undulose lamination
planar lamination
graded bed
silt/mud
sand
gravel
fault zone

The primary sedimentary structures present indicate deposition from turbidity currents, although no complete Bouma sequences (Bouma, 1962) were observed. Current ripples are common, occurring within discrete bedded units, and also as isolated, starved ripples. Horizontal lamination is frequently developed in beds of all but the coarsest grain sizes. No evidence of physical re-working of bed tops, that might indicate possible bottom or contour currents, was seen.

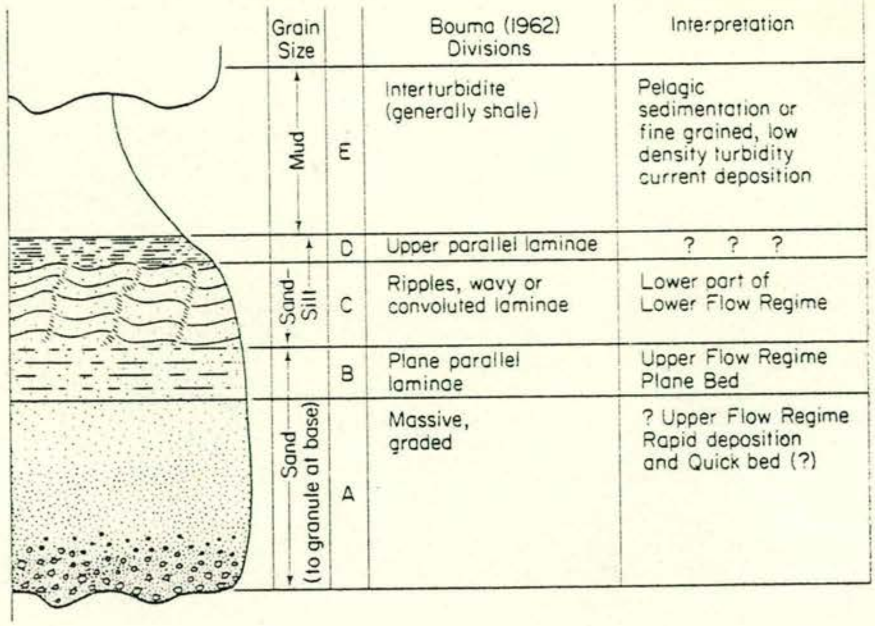
Petrographically these horizons are highly immature, both texturally and compositionally; grains and clasts are poorly rounded, and there is a high proportion of unstable lithic detritus. A mud matrix is present.

The crude coarsening and thickening-upwards sequence seen in this section indicates, according to the predictive Bouma model, increasing current velocities and increasing sediment load. The thin, rippled and parallel laminated sands are composed of Bouma divisions B & C and C, with the D & E divisions well developed, represented by the interbedded siltstones, Fig. 5:3 (left hand log). The coarser grained units, however, generally contain A or A & B divisions. Figure 5:4 shows the relationship between the internal structure of a turbidite bed, the velocities of the currents from which it was deposited, and the positions such deposits might occur in a submarine fan complex.

In the broadest sense the thin sandstones may be considered to be more "distal" than the coarser grained deposits. The juxtaposition of the conglomerates and the sandstones is consistent with an interpretation of the conglomerates as filling a channel cut into the sands and fine sands with interbedded siltstones. Relationships of this type have been interpreted by Walker (1975), as typical of channels incised into the outer areas of submarine fans. Similar, coarse grained deposits, often termed fluxoturbidites (Dzulinski et al. 1959) have, however, been reported from trench slope environments by Stanley and Unrug (1972), Carter (1979), amongst others, and from delta front slopes (McCabe, 1978, Walker, 1966, Collinson, 1969) and submarine slopes of fan-deltas (Hayward, 1982).

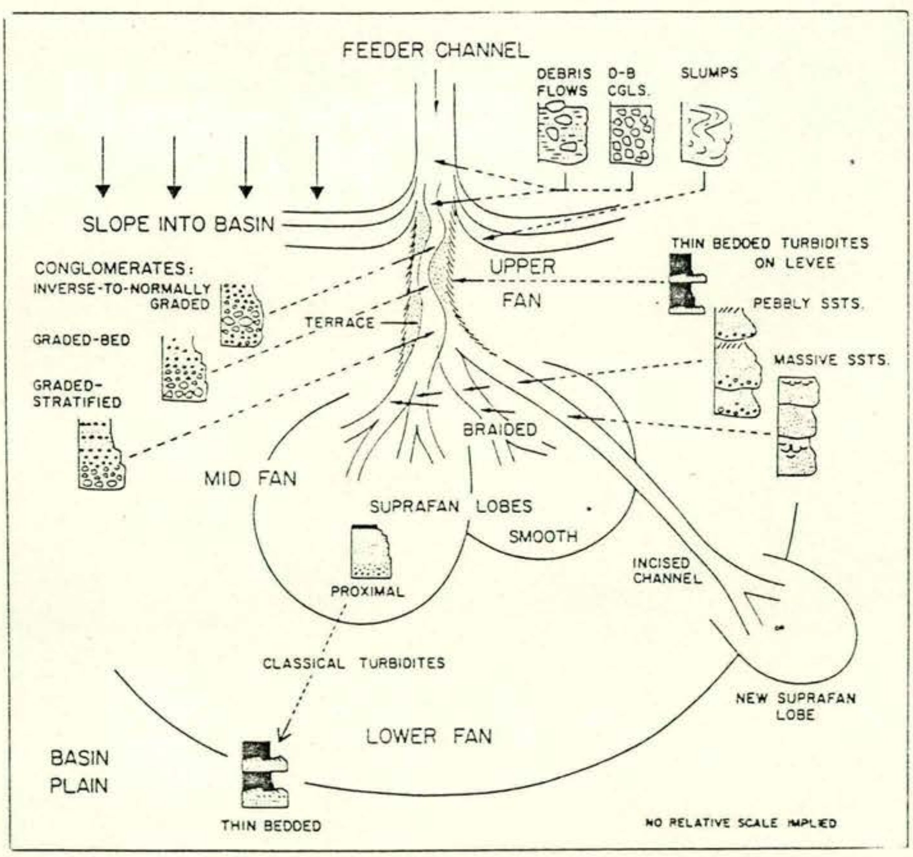
The isolated nature of the exposure in question precludes all

Interpretation of internal structures in a turbidite bed.



Ideal sequence of structures in a turbidite bed. After Bouma (1962) with interpretation after Walker (1965), Walton (1967) and Middleton (1967).

Simplified fan model (after Walker 1975)



but a very basic interpretation, i.e. that the facies is markedly different from those seen in the main areas of Conglomerate Member outcrops, and probably accumulated at a greater distance from the source area. The sequence present contains fluxoturbidites, these probably infilling channels developed in a probable slope environment, offshore from the subaerial and paralic environments already identified within the Member.

5.6 Discussion

Various observations, each being of a relatively simple nature, have been presented in the foregoing pages and simple conclusions have been made. The single most important and definite conclusion that can be made is that the Benan Formation conglomerates were most certainly not emplaced by a process of en masse sliding, as suggested by Keunen (1959), Williams (1962) and Ingham (1978). Neither are these conglomerates wholly of "probable deep water origin", (Keunen, 1959), nor deposited on deep sea fans (Anderton et al., 1979, Walton, in press). The presence of shallow marine carbonates and probable braided fluvial, possible beach deposits within the Conglomerate Member clearly refutes this suggestion.

Initial Benan Formation sedimentation in the Stinchar Valley area took place at water depths appreciably greater than those that existed during deposition of the upper part of the Stinchar Limestone Formation. Evidence provided by depth-related trilobite faunas (as per Fortey, 1974) indicate a change from inner, shallow, shelf to outer shelf conditions (see Chapter 4). The change from one regime to the other was rapid, as shown by the scarcely transitional change from Stinchar Limestone Formation to Benan Formation seen in the I.G.S. Benan Burn Borehole, Fig. 2:3, Appendix II, and Pl. 5:2. This rapid increase in water depth correlates with the Nemagraptus gracilis zone eustatic transgression, evidence for which has been provided by studies of depth related brachiopod communities (McKerrow, 1979) and oceanic sediments (Legget, 1978). Climatic ammelioration and possible glacial retreat have been adduced as casual factors (Legget, 1978, McKerrow, 1979). McKerrow also suggests that the relatively short duration of the event may preclude a possible tectonic control of the type proposed by Hays and Pitman (1973).

Whilst providing one explanation for this inferred difference in water depth, a eustatic transgression does not, however, account for the sudden, and presumably near contemporaneous, influx of coarse clastic sediments. The change in sedimentation style, from dominantly carbonate material, with low terrigenous input, to coarsely clastic must necessitate rejuvenation and uplift of an area that had, by the time carbonate deposition became well established, been significantly reduced in relief. Evidence for clastic sedimentation at the same general time as deposition of the Stinchar Limestone Formation (Chapter 6) may indicate that the site of clastic deposition had merely changed location although the time controls on the relevant sediments are unfortunately rather poor. Despite this the onset of deposition of the Benan Formation, the most geographically extensive unit in the Girvan area, is clearly an event of major importance.

The Girvan sedimentary sequence is currently considered to have been deposited in a fore-arc setting (Longman et al., 1979) (see Chaper 1). Evidence for Ordovician arc type vulcanicity, as postulated by Dewey (1971) is not however seen until the late Llandeilo/Lower Caradoc, when andesitic detritus appears in Corsewall Group conglomerates outcropping in the Rhinns of Galloway (Kelling, 1961). Radiometric dates obtained from granite clasts in the Benan Formation conglomerates indicate that cooling of the bodies from which the clasts were derived was approximately synchronous with this andesitic volcanicity (Longman et al., 1979). Both processes therefore began at roughly the same time as the earliest Benan Formation sediments were being deposited.

The intrusion of granite magmas into a presumed arc massif will serve to thicken the crust in this region with light, low-density material, thereby increasing the potential for isostatic uplift and subsequent erosion (Dickinson and Seeley, 1979). Simple, passive uplift, as a consequence of crustal thickening may now, however, be the sole mechanism responsible. In the palaeogeographic model proposed by Williams (1962) for the Ordovician sediments of the Girvan area, which is in principle borne bout by the present work, the basic concept is one of tectonic control over sedimentation, as a result of syn-sedimentary activity along normal faults, these trending S.W.-N.E., parallelling and forming the presumed 'continental margin' (see Chapter 1). In such a tectonic setting the rate at which uplift and exposure of plutonic bodies took place may be most strikingly increased. A small-scale example of the types of process involved is recorded from the island of Naxos, in the Cyclades, Greece. Here a basement complex consisting of migmatites and associated metamorphic rocks, these metamorphosed to Kyanite grade is intruded, with thermal effects, by a granodiorite body (Andriessen et al., 1979) and forms the major part of the island. The migmatites yield K/Ar dates of between 25 ± 5 m.y. and 11 m.y., indicating a prolonged cooling history, culminating in the late Miocene. The granodiorite body was intruded, with associated contact metamorphism, at 11.1 ± 0.7 m.y. (Andriessen et al., 1979). The mineral assemblages in the basement complex indicate that the highest grade rocks underwent metamorphism at 15km. depth (Roessler, 1978). Fluviatile conglomerates dated by means of freshwater gastropods as Upper Pliocene overlie the granodiorite and contain material exclusively derived from the basement complex. Miocene and early Pliocene conglomerates do not contain metamorphic material, instead are composed of sedimentary clast types. Thus between the late Miocene and the Upper Pliocene, a period of 5-6 m.y., 15km of cover had been removed from above the basement complex (Roessler, 1978). This rapid unroofing was brought about by a combination of both erosional and tectonic processes. The latter, involving relative downward movement along normal faults, developed as a result of extensional, gravitational tectonics in the Aegean area during the past 13 m.y. (Le Pichon and Anglier, 1979).

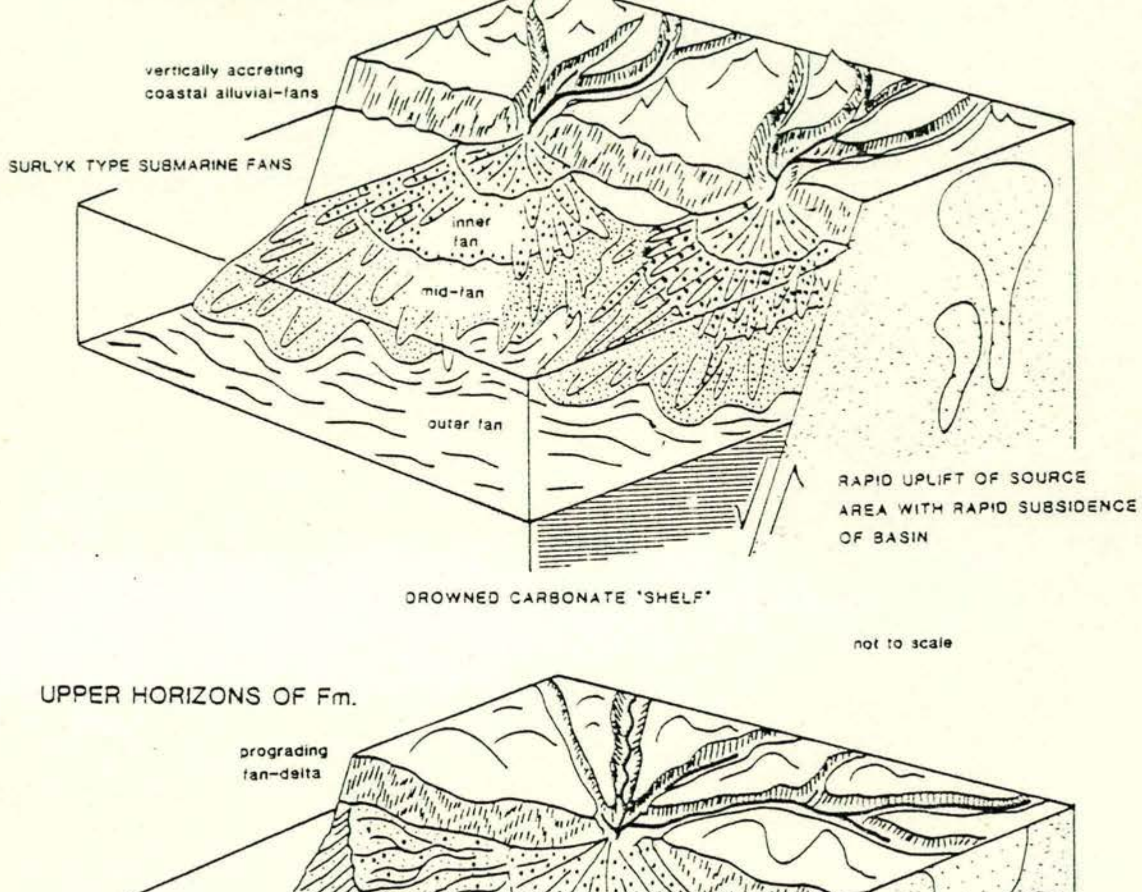
It is not suggested that there is any similarity in the extent and rate of uplift between Naxos and the Girvan area, or that the two areas developed in an idential tectonic fashion. Rather the example is cited to demonstrate the rapidity with which deep crustal levels may be exposed at the surface, if isostatic and tectonic processes are both operative.

Deposition of Benan Formation sediments in the Stinchar Valley area is therefore thought to have taken place in response to rapid uplift of a source area containing relatively recently intruded granite bodies. At the same time a eustatic transgression resulted in the drowning of a previously shallow water shelf area on which sediments of the Stinchar Limestone Formation accumulated. The various facies present, both gravel sandstone and mudstone, closely resemble those described by Surlyk (1978) from a sequence of rapidly deposited sediments interpreted as having accumulated in the submarine parts of coastal alluvial fans. Surlyk does not, however, put forward any explanation for the absence of actual alluvial fan deposits and the thick development of gravels resedimented into a marine environment. One possible explanation for this may be that the subsidence along faults controlling sedimentation was sufficiently rapid to prevent lateral outbuilding, and development of the coastal alluvial fans into fan deltas (for definitions see Appendix I). Thus any subaerial areas of a coastal fan would have been maintained at a small aerial extent and would for the most part have accreted vertically. Complementary to this it is also necessary to postulate rapid sedimentation, brought about by continual uplift of the source areas from which the gravels were derived, to maintain an area of subaerial sedimentation. Resedimentation into deeper water would be brought about by a variety of processes, including failure of oversteepened depositional slopes, mass flow processes initiated by rip currents affecting the shallower water areas, or high velocity effluent floods discharging directly into the sea. A similar setting is envisaged for the lower horizons of the Benan Formation, Fig. 5:5. Certain parts of the Formation, occurring at a higher stratigraphic level, are clearly of fluviatile/beach origin, with definite shallow water carbonate horizons also occurring. Outcrops containing fluxoturbidites chanelling into thinly bedded 'distal' turbidites, are most readily part of the same depositional system as these non-resedimented horizons. The change in sedimentary style may have been brought about by a reduction in the rate at which the basin was subsiding. At the same time the rate of sediment supply must have remained at about the same level, resulting in lateral rather than vertical sediment accumulation, and the progradation of a fan delta over the earlier, redeposited, submarine fan gravels.

Braided fluvial deposits are of common occurrence on the subaerial parts of present day fan deltas in both arid (Hayward, 1981) and humid regions (Boothroy, 1972, Boothroyd and Ashley, 1975, Boothroyd and Nummedal, 1978, Westcott and Ethridge, 1980). Shallow marine carbonates may also be distinctive components of such

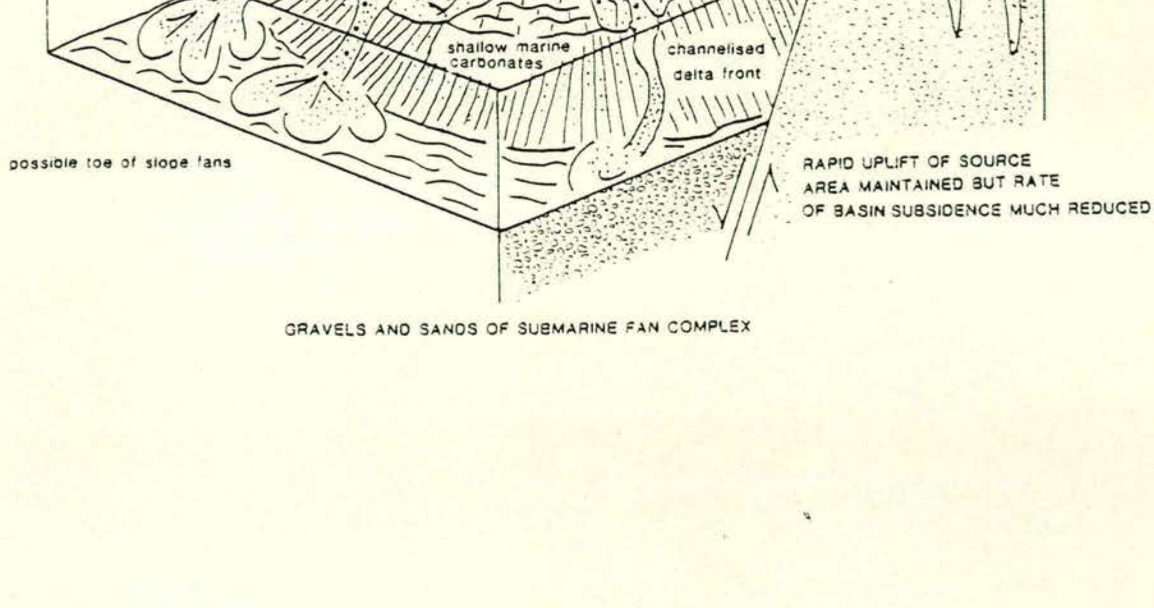
PALAEOGEOGRAPHIC MODEL FOR BENAN FM.

LOWER HORIZONS OF Fm.



not to scale

UPPER HORIZONS OF Fm.



systems (Gvirtzman and Buchbinder, 1978, Wescott and Etheridge, 1980, Hayward, 1981,1982). All authors report both fringing and patch reefs, these occurring in the shallow subtidal zones. In addition Gvirtzman and Buchbinder, and Hayward report algal and foraminiferal carbonates from back-reef, behind beach and shallow subtidal lagoons, see Appendix III. Ancient lagoonal/marginal bay sediments have also been reported by Ricci Lucchi et al. (1981) from Pliocene fan deltas in the Appenines, Italy.

Little is known about processes in the offshore regions of present day fan deltas, but a well decumented account of the submarine facies of Miocene Fan-deltas exposed in the Anatalya area S.W. Turkey, is provided by Hayward (1982). Hayward reports closely similar conglomerates/coarse sands channelling into thinly bedded sandstones and mudstones, from the submarine slope regions of the fans. Also of relevance is the model proposed by Walker (1966) for the deltaic sediments of the Shale Grit and Grindslow Shales (Carboniferous, England). The thin turbidites seen in the Water of Gregg are broadly similar to those seen in the Shale Grit, and are similarly interpreted as non-channelised deposits accumulating on the (fan) delta slope. The fluxoturbidites most probably represent delta slope channels along which sediment may have been transported to small base of slope submarine fans.

It is fully realised that much more work needs to be carried out before a proper interpretation of the Benan Formation can be made, in the meantime the present model, as summarised in Fig. 5:5, is felt to be consistent with the evidence so far gathered.

CHAPTER 6

THE TAPPINS GROUP:
LOCALITIES BETWEEN THE STINCHAR AND GLEN APP FAULTS

6.1. Introduction

To the south of the Stinchar Valley fault complex the sequences that typify the Barr Group are not recognizable. Instead the sections available for study are largely dominated by greywacke turbidites and associated mudstones and conglomerates. Fossil faunas are exceptionally scarce, and thus the age relationships in what is a structurally and sedimentologically complex set of rocks cannot be determined. In addition correlation with the Barr Group is impossible using biostratigraphic methods. In Chapter 5, however, certain horizons have been correlated with the Benan Formation. Conglomerate Member, on lithological grounds, similarly, reddened limestones exposed on Doularg Hill (NX29 2660 9240) have been correlated with the Auchensoul Limestone Member, Williams (1962).

Since the advent of plate tectonic theory and the development of refined concepts of continental margin sedimentation (Burke and Drake, 1974), many authors have compared the Southern Uplands of Scotland with ancient and recent accretionary prisms seen elsewhere in the world (Mitchell and McKerrow, 1975, McKerrow et al., 1977, Legget, 1980, Legget et al., 1979, 1980, 1982). In the context of this model Legget et al. (1979) and Legget (1980) have interpreted the sequences outcropping between the Stinchar and Glen App faults as the oldest thrust slice within the accretionary prism. Furthermore, Dewey (1971), Piper (1972) and Legget (1980) interpret the sediments as turbidites deposited within an oceanic trench. It is apparent that, in light of Chapters 3, 4 and 5, where Barr Group sediments are demonstrated to be shelf deposits, the above interpretation does not allow for the presence of any intervening slope deposits. It was the intention, during the present study, to carry out a detailed sedimentological investigation of those sequences available, with the objective of resolving the above mentioned problem, and attempting, if possible, a correlation with the Barr Group.

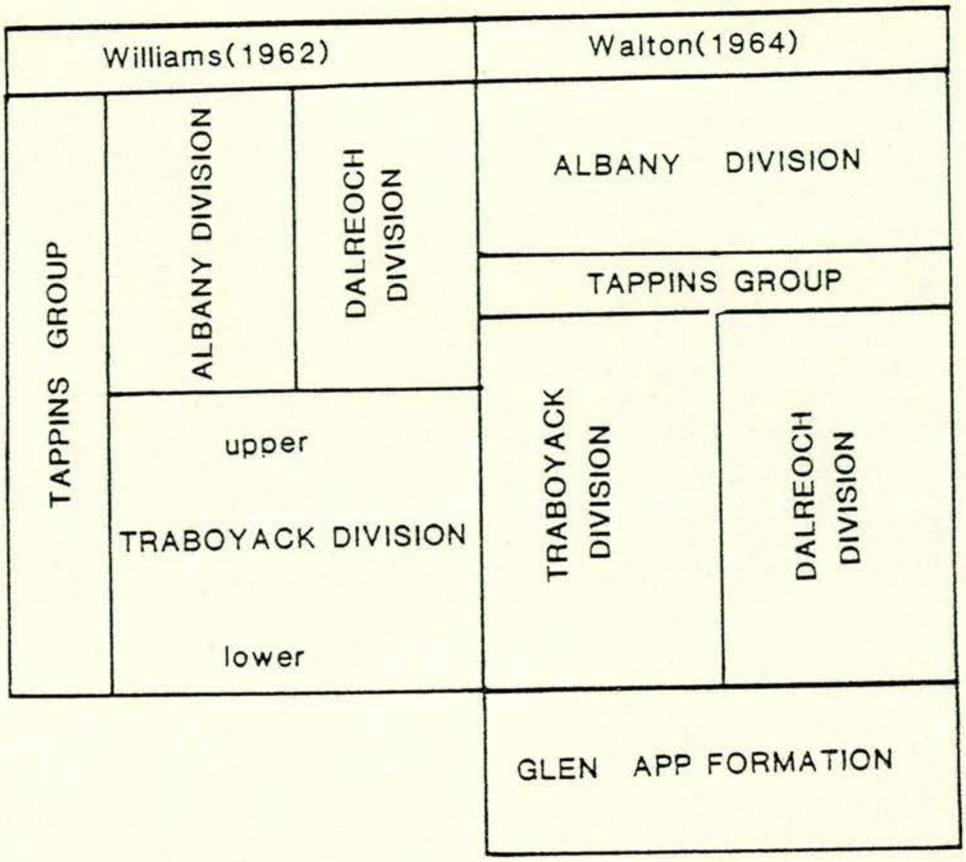
For reasons of time it has not yet been possible to carry out a detailed petrographic study to back up the field data presented herein. For this reason this report must be regarded as a reconnaisance, rather than a final, conclusive statement. Neither has it been possible to combine this study with that currently being carried out by other workers (A.H.F. Robertson and J.K. Legget) on rocks in the same tectonic slice, but outcropping further to the south-west, although it is intended to collaborate on this problem in the future.

Stratigraphy - Previous Work

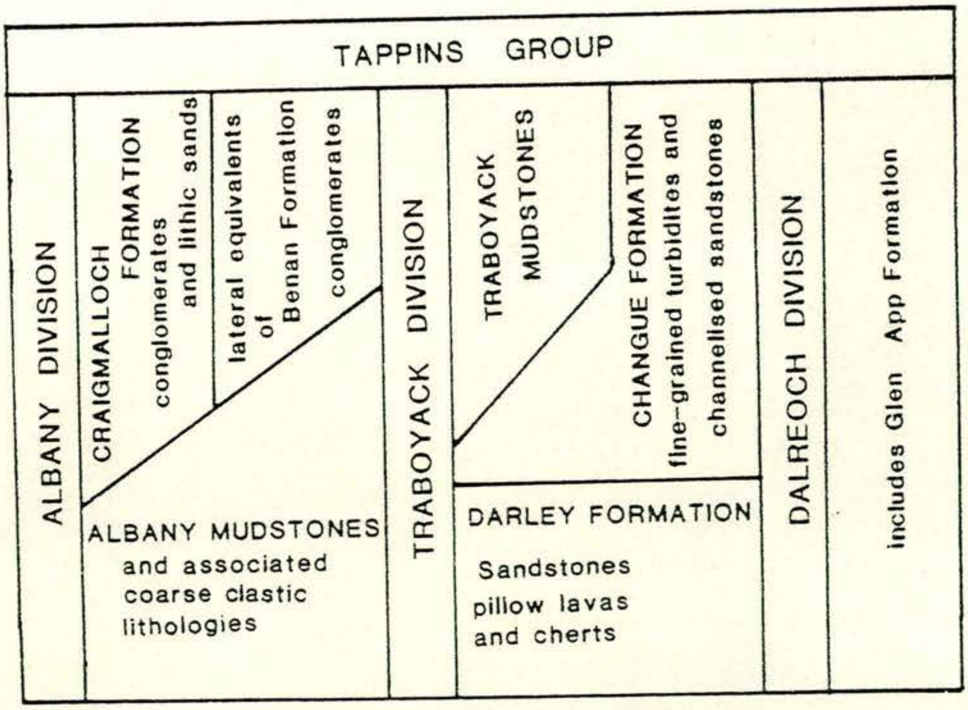
Peach and Horne (1899) assign all the rocks between the Stinchar and Glen App faults to the N & S, and Portandea and Tappins Hill to the W & E, to the Tappins Group. The sequence was thought to be not more than 500' thick but extensively thickened by isoclinal folding. Williams (1962) subdivided the Tappins Group into three component divisions as shown in Fig. 6:1a but recognised the need to retain the original sense of the term, having previously employed a somewhat confusing meaning (Williams, 1959). Walton (1961, 1965) presents a modified stratigraphy that does not apparently take the original definition into account. The redefined Tappins Group is distinguished on lithological grounds from a supposedly older Glen App Group (Walton, 1961). Three years later (Walton, 1964) the Glen App Group becomes the Glen App Formation and the Tappins Group taken to consist only of the Dalreoch and Traboyack divisions of Williams (1962). The Albany Division was not included as part of the Tappins Group. The same usage summarized in Fig. 6:1a is also employed by Whittington (1976), who states that Walton (1965) considered the Dalreoch and Trayboyack Divisions to be lateral equivalents of the Tappins Group.

In view of the confused nature of these most recent stratigraphic schemes, the present work will employ a modified version of Williams (1962) stratigraphy as shown in Fig. 6:1b and defined in the following section.

Previous stratigraphies of the Tappins Group.



Proposed stratigraphy of the Tappins Group.



Proposed Stratigraphy

During the course of the present research the author realised that existing stratigraphic schemes did not allow the recognition of lithological variations within the previously defined units. The informal scheme proposed in Fig. 6:1b goes some way towards remedying this situation, but does not deal with any sediments previously assigned to the Dalreoch/Glen App stratigraphic units. As the scheme is intended only for use in the current work the type sections are not formally designated but are described in the account of the relevant exposed section. No relative ages between the three Divisions are implied in Fig. 6:1b. However, field relationships suggest that the Traboyack Division is most probably older than the Albany Division, in agreement with previous authors. Furthermore, within the Traboyack Division the Traboyack mudstones are, at least in the upper part, probably younger than Darley Formation. The Darley Formation and Changue Formation may in part be lateral equivalents. In the Albany Division it is possible that the Albany mudstones and Craigmalloch Formation Conglomerates are lateral equivalents, on the basis of new faunal information. Certain parts of the Albany Division as mapped by Williams (1962) are interpreted as lateral equivalents of the Benan Formation and are assigned to that unit (see Chapter 5).

6.2 Traboyack Division

6.2.1 Darley Formation

Thickness: approximately 900m.

Type locality: Uppermost reaches of Water of Gregg, between waterfall 200m upstream from the junction with Laggan burn and Glen App fault zone near Darley (NX29 2980 9180), Fig. 6:2.

Lithologies: The lowermost lithological units in the Formation are well bedded red cherty mudstones associated with vesicular pillow lavas (Plate 6:1, Figs. 1 & 2). Above these a thick sequence of sandstones forms the remainder of the Formation. Lower horizons within this sequence consist of 2-3cm thick graded sandstones with thick interbedded mudstone and siltstone units (Plate 6:1, Fig. 3). Grain size and bed thickness increase upwards,

GEOLOGICAL MAP -WATER OF GREGG

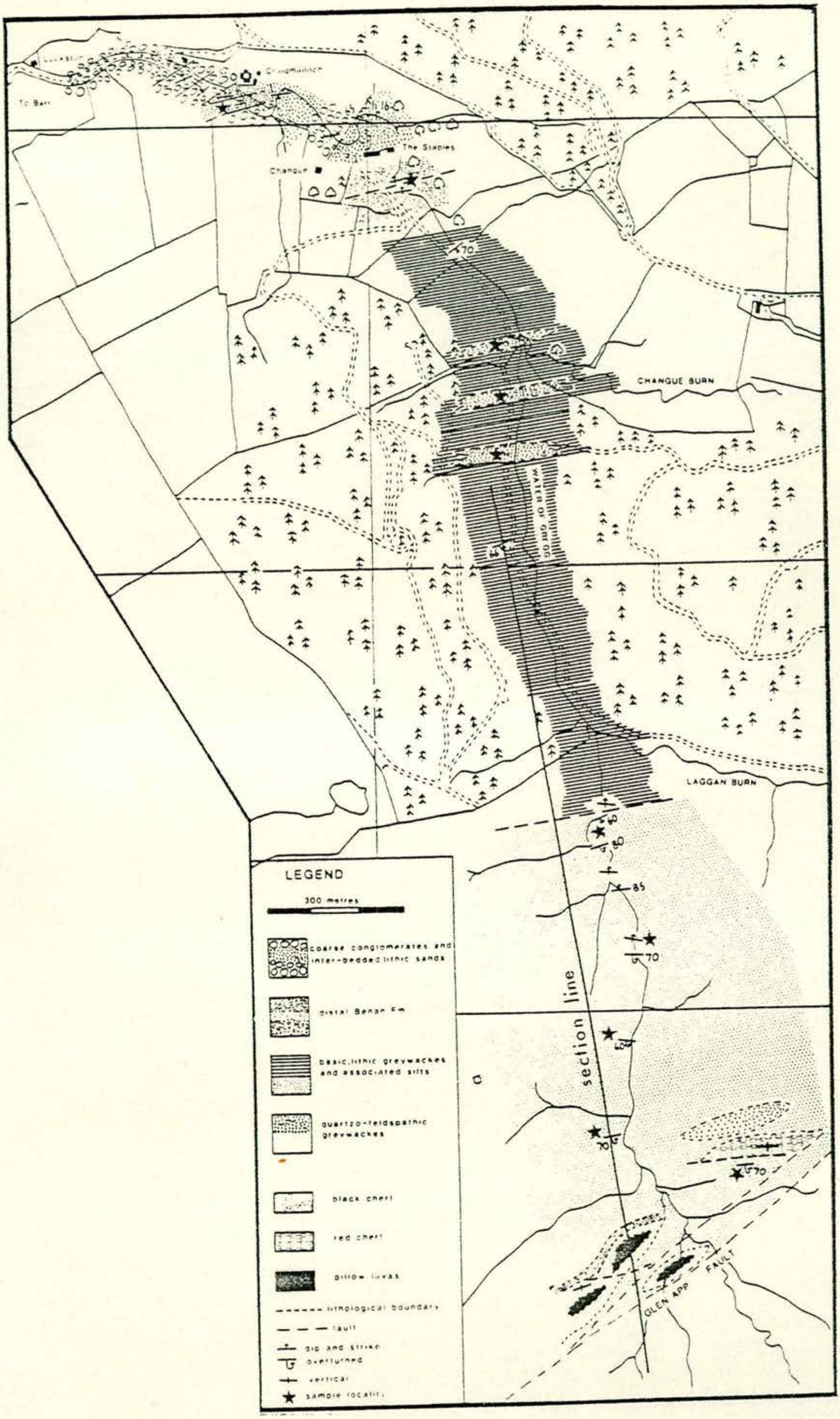


Plate 6.1

Figure 1.

Southerly dipping, thinly bedded, cherty red mudstones of Darley Formation outcropping in tributary of the Water of Gregg (NX29,294 913). These sediments occur in close proximity to a sequence of basaltic pillow lavas.

Metre stick gives scale.

Figure 2.

a) Photomicrograph of cherty mudstone showing the presence of probable radiolarions (arrowed a) and the highly veined (silica) nature of these sediments.

   Thin section, GW/12/81, plane polarised light.

b) Photomicrograph of vesicular, finely feldsparphyric basaltic lava. The vesicles are silica infilled as are the irregular tension veins. Thin section, GW/11/81, crossed nicols.

Figure 3.

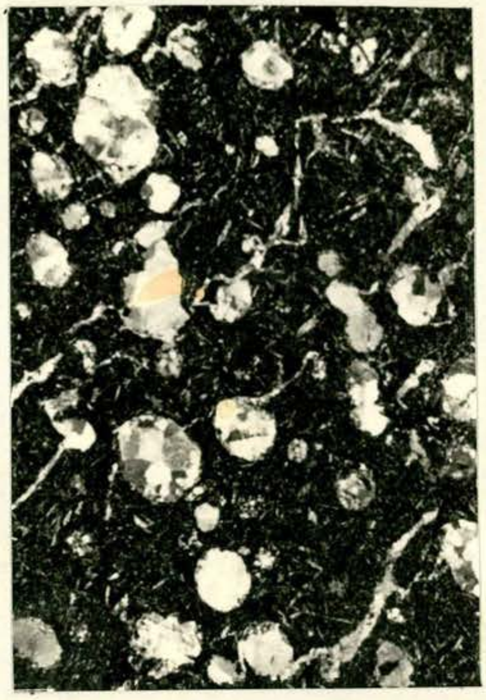
Thinly bedded, lenticular, fine sand turbidites in silt dominated, lower, part of Darley Formation, which generally becomes coarser grained up sequence.

Locality, (NX29,295 917) Water of Gregg near Darley Farm.

Plate 6.1

Figure 1

0.6mm



1.7mm

Figure 2a

Figure 2b

Figure 3

the topmost horizons being 0.5m thick beds of granule conglomerates.

The Darley Formation is distinguished from the Changue Formation on the basis of petrography, being quartzo-feldspathic rather than lithic (Fig. 6:3), and of overall facies types (Section 6.2.1a).

6.2.1a Sedimentology

The pillow lavas and associated cherts that occur at the base of the sequence have been compared with present day oceanic lavas, and sediments (Legget et al., 1979, 1982). Pillow lavas also occur at the base of the four Ordovician tectono-stratigraphic units that constitute the Northern Belt of the Southern Uplands (Legget et al., 1979). Trace element geochemistry indicates that these dominantly basaltic lavas are of oceanic affinity (Lambert et al., 1981). The Darley formation lavas may be similar, although no analyses are available.

Paleocurrent data (Fig. 6:4) indicates that the turbidity currents from which the overlying sandstones were deposited flowed from the north-east, parallel to the continental margin, rather than down an inferred S.E. facing slope.

At the top of the Darley Formation the sandstones, which elsewhere young to the north are seen to young to the south, denoting the presence of a near isoclinal syncline with a subhorizontal axial plane dipping to the south (Fig. 6:5) and, perhaps a horizontal hinge. The juntion with the overlying Changue Formation is complex, containing a thick disturbed zone (Plate 6:2, Fig. 1) in which muds, sands and granule conglomerates are interfolded in a complex fashion that suggests that the sediments were plastic, rather than brittle and lithified, when deformation took place (Plate 6:2, Fig. 2). In addition to the disturbed and deformed zone, a small-scale, upright, near isoclinal anticline (Plate 6:2, Fig. 3) is also seen, this being the sole example of a relatively small scale fold structure seen during the present study. The possible significances of this junction will not be discussed here but are reviewed in a more general context in section 6.4.

Figure 6.3

QFR Diagram for Darley and Changue Sandstones.

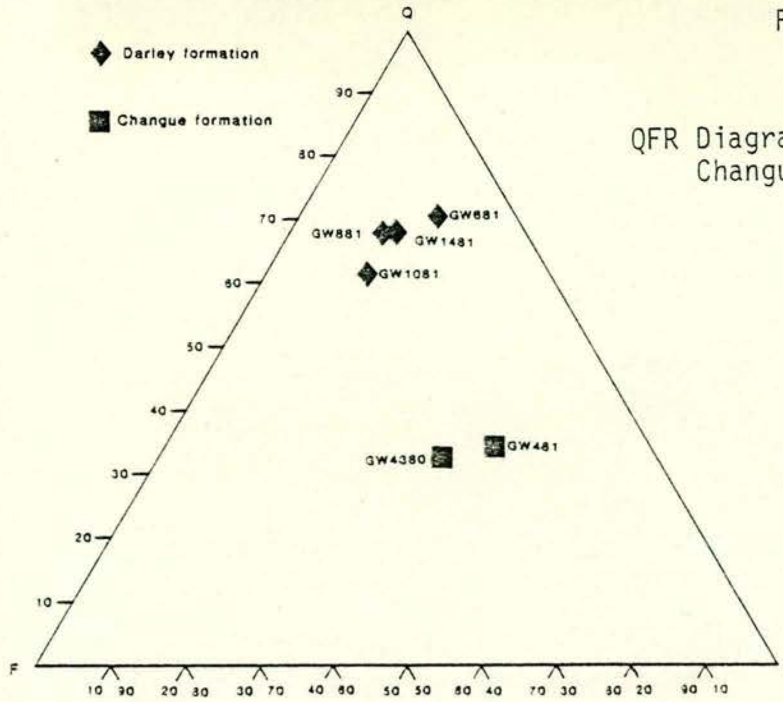


Figure 6.4

Darley Formation Palaeocurrents.
based on 16 Flute cast readings

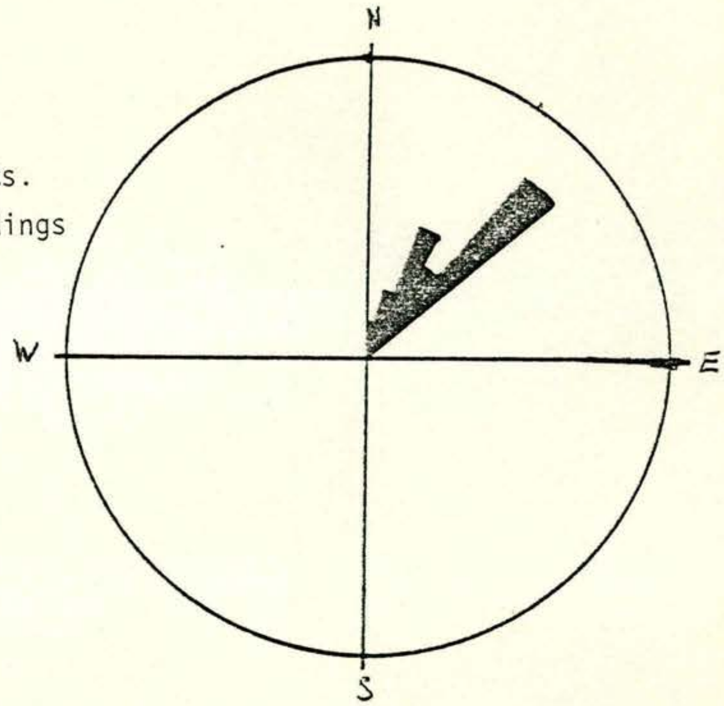


Figure 6.5

Diagrammatic cross-section along Water of Gregg.

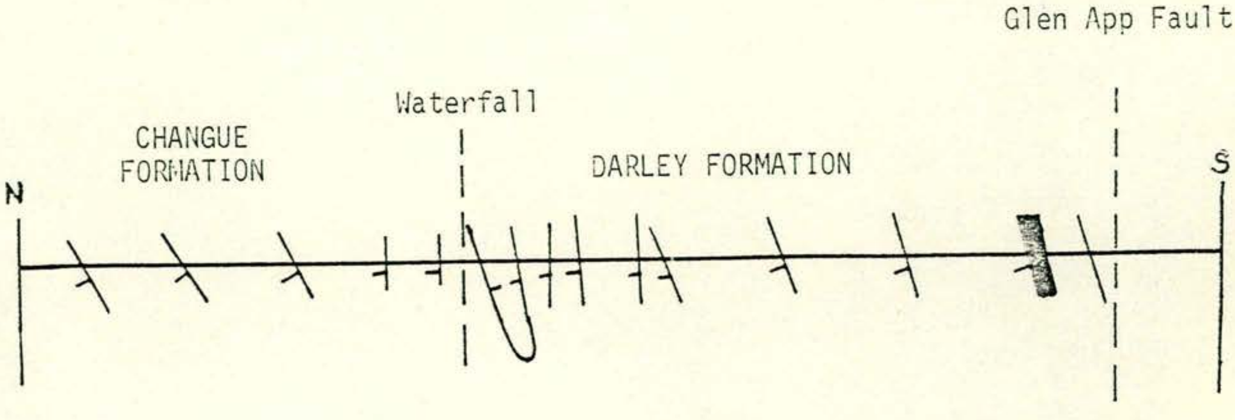


Plate 6.2

Figure 1.

Topmost part of Darley Formation, on left of photograph, consisting of thickly bedded coarse sand turbidites, here folded into a light near vertical anticline. The disturbed junction with the overlying Changue Formation is marked by the prominent ridge marked a.
Locality, Waterfall, Water of Gregg (NX29,295 924).
Scale is given by rucksack in foreground.

Figure 2.

Detail of junction between the Darley and Changue Formations. The horizon consists of chaotically admixed sands and mudstones (labelled a).
Locality, Waterfall, Water of Gregg (NX29,295 924).
Scale is given by knife, 12cm long.

Figure 3.

Detail of tight anticline formed in thickly bedded turbidites of the topmost Darley Formation. The left-hand limb is overturned, forming the northerly limb of a larger synclinal structure developed in lower horizons of the Formation.
Locality, Waterfall, Water of Gregg (NX29,295 294).
Scale is given by tree in centre of frame which is approximately 10' high.

Plate 6.2

Figure 1

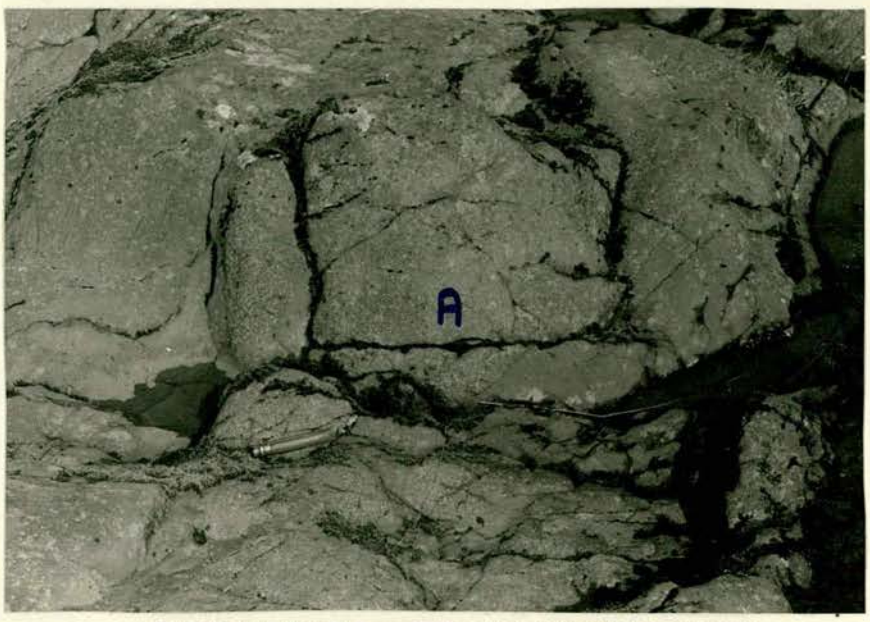


Figure 2

Figure 3

6.2.2 Changue Formation

Thickness: approximately 1000m

Type section: Water of Gregg from Waterfall (NX29 2945 9240) to 100m upstream from The Stables (NX29 2925 9365).

Lithologies: The lowest horizons of the unit outcropping in the Water of Gregg between the waterfall already mentioned and the junction with Laggan Burn, are vertical thin bedded 2-5cm, turbidites (Plate 6:3, Fig. 1). The faulted contact with the Darley Formation is complex and is discussed in section 6:4. Downstream from the junction of the two streams the lithology is somewhat different. Overturned, moderately thickly bedded, dark mudstones (Plate 6:3, Fig. 2) are interbedded with thick, massive sandstones. The formation is in general very poorly exposed and prevents a more detailed description. The unit also outcrops in the upper reaches of Albany Burn (Fig. 6:7).

6.2.2a Sedimentology

The Changue Formation comprises faintly graded silty fine turbidites interbedded with coarse, massive, sand and granule turbidites. The lowermost horizons of the formation as seen in the Water of Gregg are composed of relatively thinly bedded, graded fine sand turbidites, lacking C divisions and possessing very well-developed red mudstone D/E divisions (Plate 6:3, Fig. 1). Downstream, but up-sequence, above the junction of the Water of Gregg with Laggan Burn the dominant, lithologies are dark, nearly black silty mudstones (Plate 6:3, Fig. 2), which at this point are overturned, dipping to the south, but younging to the north, but by thick, massive sandstones. These sandstones become more coarse-grained up-sequence, those found towards the top of the formation being granule conglomerates. One such unit contains a well-developed ball and pillow structure (Plate 6:3, Fig. 3).

Sandstone units may be 15-18m in thickness, but unfortunately it is not possible to trace them through the poorly exposed, afforested or pasture areas. Thus the lateral extent and nature of the margins of these units cannot be determined.

As with the Darley formation it is not possible conclusively to define a particular depositional environment for the Changue

Plate 6.3

Figure 1.

Thin parallel sided fine sand turbidite of Changue Formation with thick hemi-palagic divisions (showing dark here) consisting of reddish-purple silty mudstone. The turbidites consist only of the Bouma A division, and have slightly erosive and loaded bases.

Locality, Water of Gregg between waterfall and junction with Laggan Burn (NX29,295 925).

Hammer handle (18cm) gives scale.

Figure 2.

Highly fractured section through highly argillaceous silty very fine sand turbidites of the Changue Formation. The sequence is overturned, graded bedding where visible indicating younging to the right (northwards).

Locality, Water of Gregg, downstream from junction with Laggan Burn (NX29,293 929).

Metre stick gives scale.

Figure 3.

Ball or pillow structure in thick, massive, coarse grained sandstone possibly infilling channels in the finer grained sediments shown in previous figure.

Locality, Water of Gregg (NX29,293 993).

Hammer (30cm) gives scale.

Plate 6.3

Figure 1

Figure 2

Figure 3

formation exposures in the Water of Gregg and Albany Burn. Various possibilities are, however, worthy of consideration.

Comparable sequences occurring in the Eocene "Poway" conglomerate of Southern California have been interpreted as the product of infilling of submarine channels by coarse clastic material transported down-slope by mass-flow processes (Howell and Link, 1979). These channels were interpreted as heading in the shallow water areas of a fan delta, in a manner compared with the present day Scripps Canyon which heads within 100m of the surf zone. Hayward (1982) places the same interpretation on channelized coarse sands and gravels of the Kemer Formation, S.W. Turkey that similarly occur in the distal, downslope,although in relatively shallow water, areas of a fan-delta. Collinson (1970) and McCabe (1978) describe massive, laminated, cross-stratified sands infilling delta-front channels in Carboniferous sediments of N. England. In all the examples noted above the channels are incised into turbiditic sands and silts that are markedly finer grained than the channel fill, which may consist of pebbly mudstones, sandstones, conglomerates and slump units of various lithologies. The dimensions of these fossil channels are variable, those described by the above authors being not more than 50m thick by up to 500m in lateral extent. These channels are noticeably smaller than the submarine canyon fills described by Almgren (1978), these being up to 750m thick and up to 10 miles in lateral extent.

Alternatively, rather than representing channel-fill deposits the massive sandstones may equally well represent non-channelized turbidites, as no channel margins are seen. Certainly, the fining upwards sequences considered typical of channel-fill deposits (Walker, 1978) were not seen. At the same time the thickness of these sandstone units is considerable, and if they do represent non-channelized, sheet-flood, turbidites the flows from which these sediments were deposited must have been exceptionally large, as no multiple grading, indicative of amalgamation, was recognised.

Despite a lack of observational evidence, a channel-fill interpretation is preferred; the sandstones being apparently similar to fluxoturbidites (Dzulinski et al., 1959) and massive, structureless, sands (Walker, 1978) both of which occur as infillings in slope and proximal fan channels (Rupke, 1978).

Thus the sandstones may represent part of a submarine fan complex occurring in channels supplying sediment to lobes developing in the outer fan regions, or alternatively they may have been deposited within small scale slope channel.

As already stated it is not possible to determine in which of these settings the Changue Formation accumulated. There is, however, a degree of overlap between the two situations, submarine fans develop most frequently at the base of a submarine slope, the sediment flows rapidly losing velocity as they leave the confines of the submarine canyon or valley through which detritus is re-sedimented from shelf areas. It may therefore be difficult to distinguish, even in a well exposed sequence, between the lower reaches of a slope channel and the upper reaches of an inner fan valley.

6.2.3 Traboyack mudstones

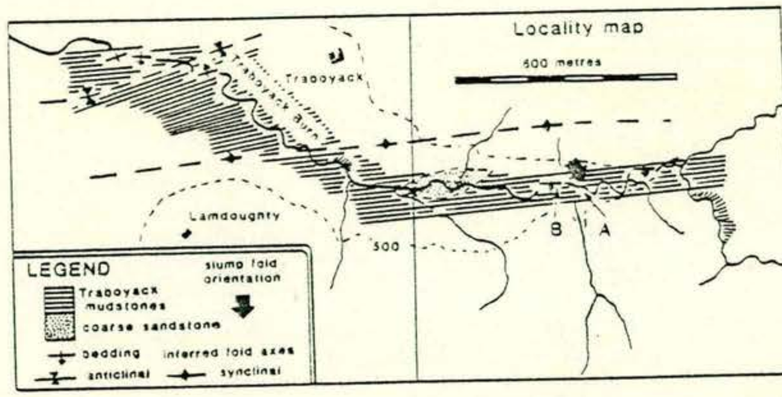
Thickness: 600m + as exposed but has probably been tectonically thickened by upright, near isoclinal folding, Fig. 6.6.

Type section: Traboyack Burn as shown in Fig. 6:6.

Lithologies: Highly distinctive laminated and thinly bedded greenish sands grading to and interbedded with red, haematitic non-cherty mudstones (Plate 6:4, Fig. 1). Thicker turbidite units and slumped horizons also occur (Fig. 6:6). Williams (1962) reports the occurrence of a 200m thick laterally persistent conglomerate unit within the Traboyack mudstones. This could not be located in situ but boulders of it were found in the stream bed. These consisted of pebbles and small cobbles of basalt and chert with abundant red and green mudstone rip up clasts (Plate 6:4, Fig. 2). A less well-exposed section through the unit is seen in Drummellie Burn and a thin in-faulted sliver of the mudstones occurs in Albany Burn (Fig. 6:7).

Age: No fossils have been recorded from this unit. Williams (1962) considers it to be both older than (Table 1, p.56), and laterally equivalent to (p.63, para. 3 and Fig. 5, p.57) the Kirkland Formation. Evidence is put forward in Section 6.2.3a that suggests that there are sedimentological reasons for considering lateral equivalence with the Kirkland Formation likely.

TRABOYACK BURN MEASURED SECTIONS



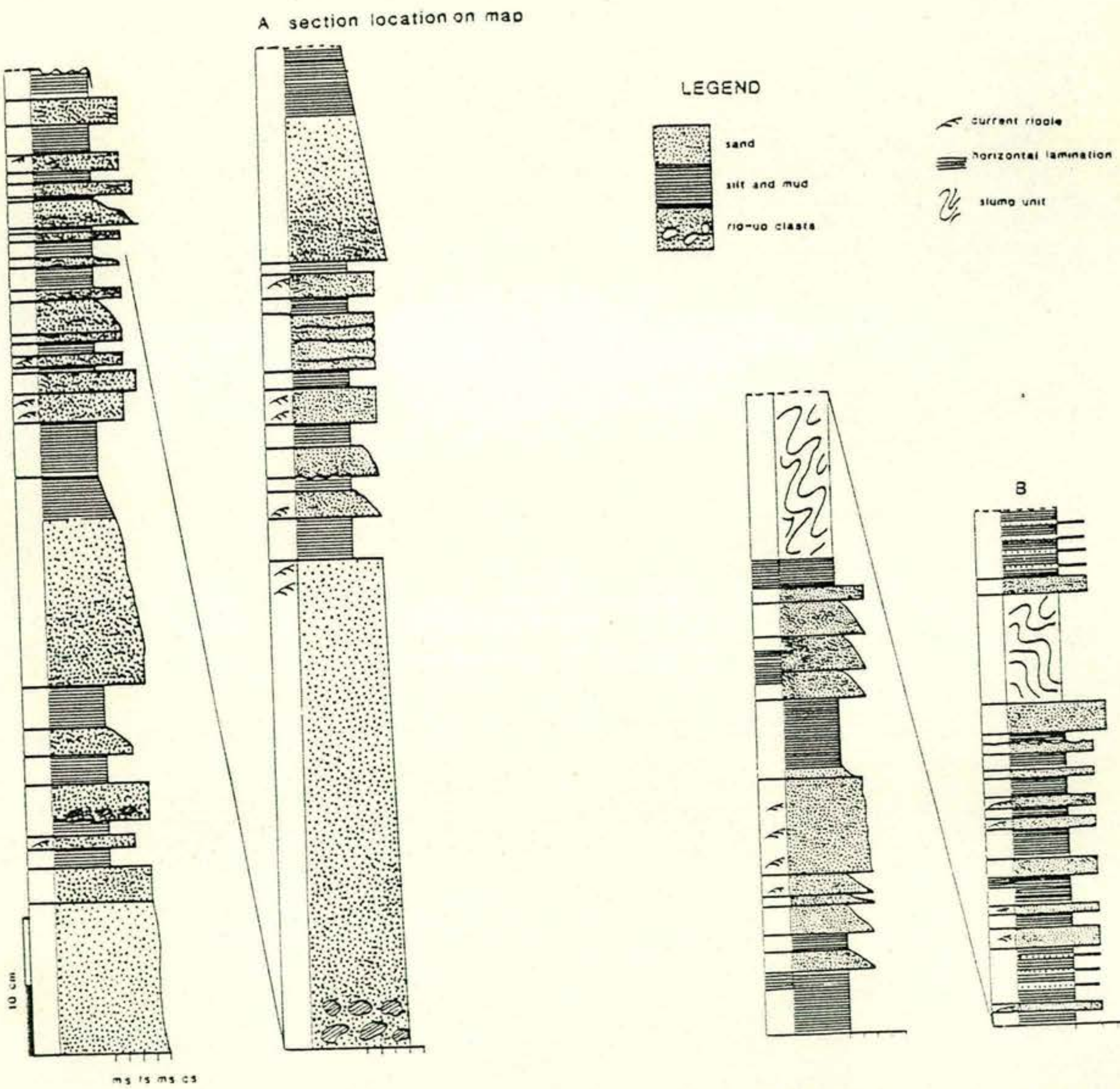


Figure 6.7

GEOLOGICAL MAP - ALBANY BURN

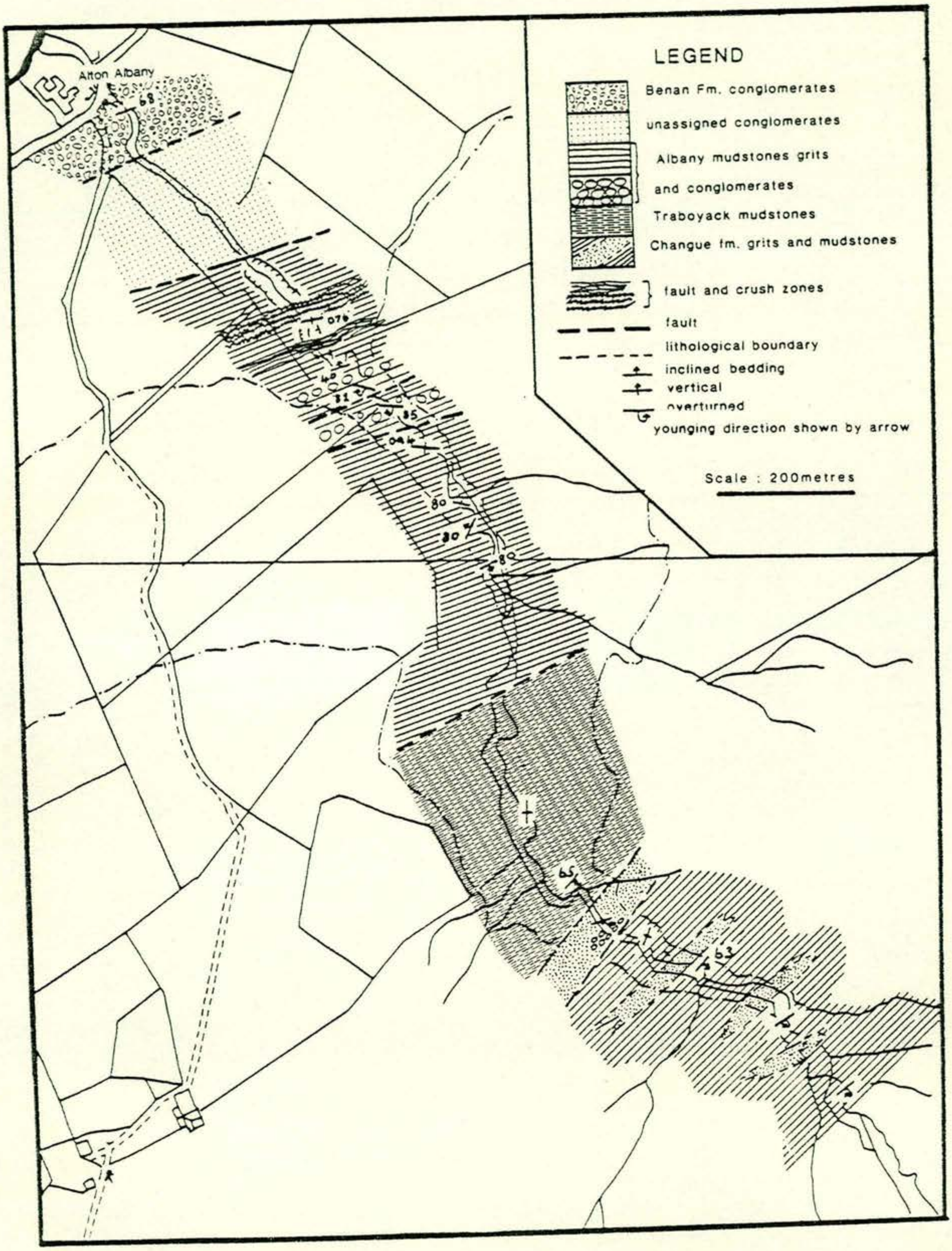


Plate 6.4

Figure 1.

Thinly bedded very fine sand turbidites of the Traboyack Mudstone Formation. The individual sandstone beds are of centimetre scale and are generally persistent within outcrop, although lateral thinning can be seen in some instances.

Locality, Traboyack Burn (NX29,265 915).

Scale is given by tape measure (5.5cm across).

Figure 2.

Pebble of conglomerate containing abundant rip-up clasts of Traboyack Mudstone Formation sediment (arrowed a).

Specimen, TB6/80, loose block Traboyack Burn.

Figure 3.

Cut surface, specimen from argillaceous horizon of Traboyack Mudstone Formation. The sandstone beds show the typical horizontal or slightly undulose lamination (a) and faintly lensoidal, rippled horizon (b).

Specimen, TB8/80, Traboyack Burn.

Plate 6.4

Figure 1

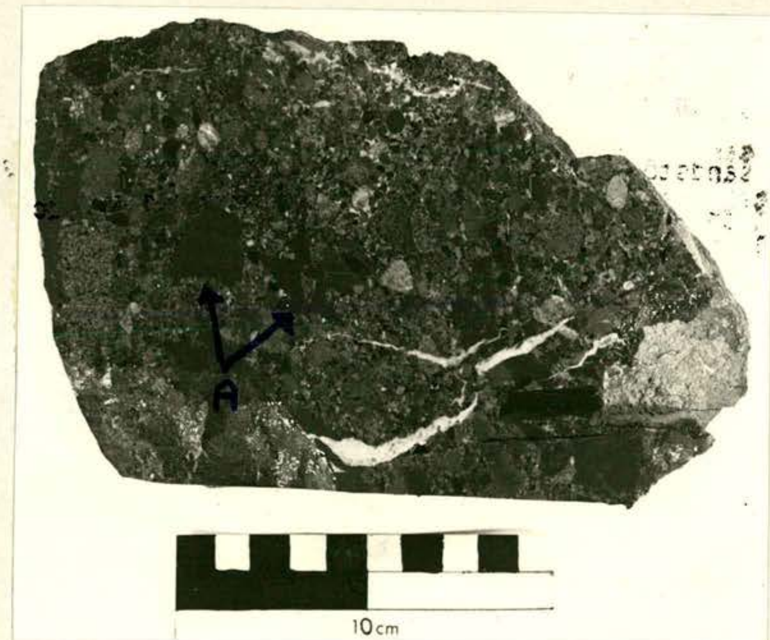


Figure 2

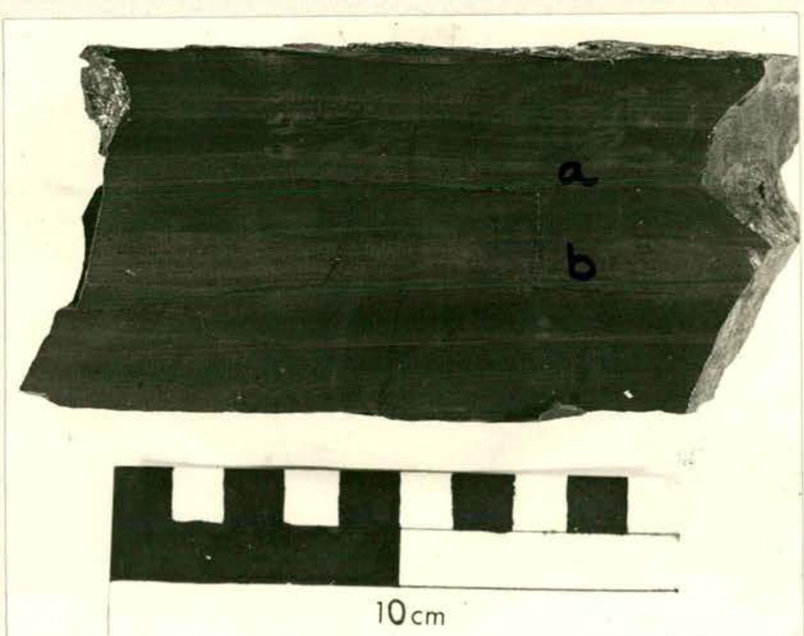


Figure 3

6.2.3a Sedimentology

Figure 6:6 shows two detailed sections through the red mudstones and interbedded, green, fine to coarse sandstones that constitute this unit. The dominant facies present is thinly bedded sands and silty muds (Plate 6:4, Fig. 1). The sands may be horizontally laminated, occurring as individual horizons (Plate 6:4, Fig. 3) or occurring as the lower part of a couplet, with the upper part represented by a rippled horizon (Plate 6:5, Fig. 1). Rippled sands may occur as individual, starved ripples (Plate 6:5, Fig. 2) or as thicker, more complete cross-stratified units (Plate 6:5, Fig. 3), and also in association with laminated sands as outlined above. The bases to the sandstone horizons may be planar, non-erosive, scoured or scalloped (Plates 6:4 & 6:5). Bed tops are in general clearly defined. Bedded sands, 10-30cm in thickness are simply graded, possess no internal sedimentary structures (Fig. 6:7) and may contain rip-up clasts of the red mudstones into which they are erosive. The interbedded red mudstones are generally structureless, but may contain very fine sand laminae. Slumped horizons consisting of the thinly bedded facies were recognised at two points in the measured sections. The laterally persistant conglomerate horizon reported by Williams (1962) was not encountered during the present study. Loose blocks of conglomerate containing rip-up clasts of the mudstones (Plate 6:4, Fig. 2) were, however, found in the stream bed.

The sandstone horizons are all interpreted as the result of deposition from turbidity currents. Current turbulence is indicated by scouring of the underlying sediments and the presence of graded beds and beds consisting of both parallel laminated and rippled units are consistent with the Bouma (1962) turbidite model. The interbedded red silty muds are thought to have been deposited by fall out from suspension, only in a few instances was a gradation from sand to silty mud observed. The thin sand laminae within the muds may have been deposited from small scale turbidity currents or from bottom currents. The conglomerate body reported by Williams may represent a channel infill.

Whilst there are many turbidite sequences recorded in the literature, those felt to be most closely comparable to the Traboyack Mudstones are the red argillite rock type of Winston (1978),

Plate 6.5

Figure 1.

Detail showing variety of sedimentary structures present in turbidites of the Traboyack Mudstone Formation. The thick bed in the centre of the slab contains Bouma divisions B and C whilst the remaining sand horizons are planar laminated.
Locality, Traboyack Burn. Scale is given by pen (13cm).

Figure 2.

Thin turbidite horizons in Traboyack Mudstone Formation. The horizon A may have been deposited from a turbidity current (Bouma division C) or alternatively may have resulted from reworking by bottom currents.
Locality, Traboyack Burn. Scale given by coin (2.3cm).

Figure 3.

Relatively thickly bedded turbidites in sandier part of Traboyack Mudstone Formation. The beds consist of Bouma divisions A,B,C abd D, although not all are present in a given bed. Bed bases are erosive and sometimes loaded.
Locality, Traboyack Mudstone Formation. Scale is given by coin (2.3cm).

Plate 6.5

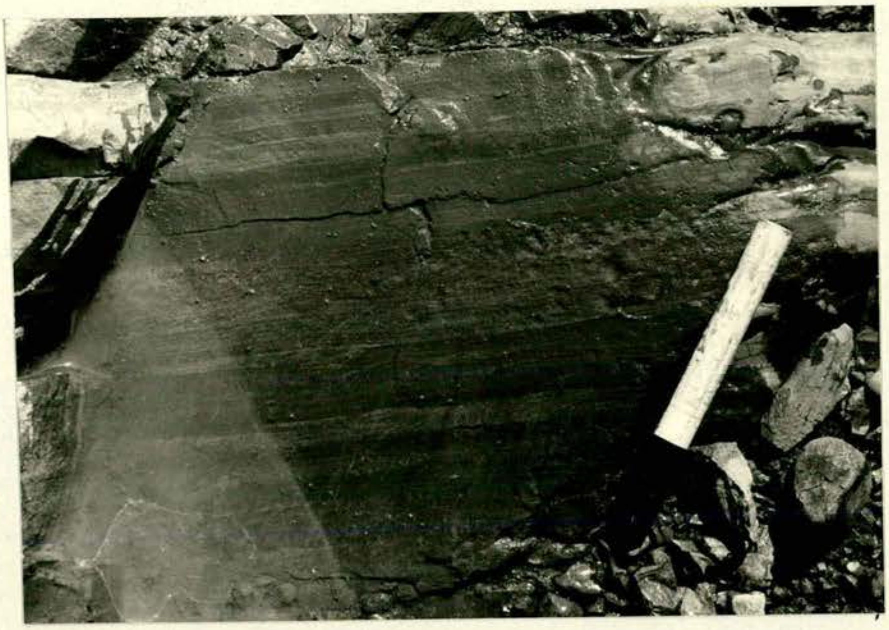


Figure 1

Figure 2

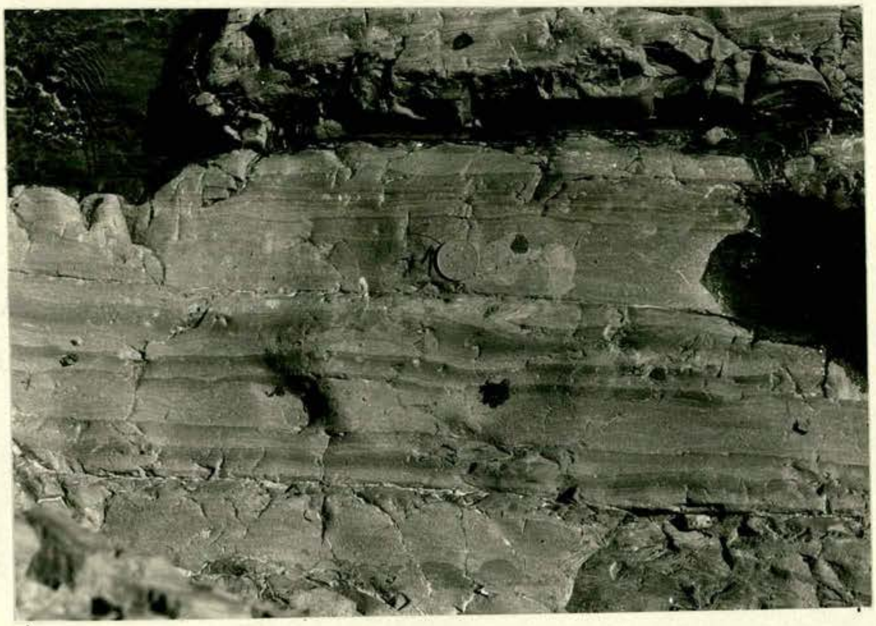


Figure 3

the finely-bedded siltstones and shales figured by Eriksson (1978 Fig. 13; p.301) and thinly bedded fine sandstone, siltstones and mudstones described by Steel and Aasheim (1978). Whilst there are various points of similarity between these instances there are also significant differences and there is no possibility of a comm· ıode of formation. It is perhaps significant that all o ·ur as part of a fan-delta facies assemblage, occurring in subaqueous, marine (Winston 1978) or lacustrine setting (Steel and Aasheim, 1978). In the example from the Archean Moodies Group, Barberton Mountain Land, South Africa, described by Eriksson (1978) the author suggests an overbank setting, as part of a high sinuosity meandering river system deposition occurring by fallout and from traction as bed load. There deposits occur in the distal areas of a coast fan-delta, the proximal reaches of which are characterized by conglomerates deposited in a braided-fluvial system. In the present author's opinion, the description given by Eriksson is not necessarily consistent with his interpretation and at least some of the graded beds mentioned could as readily be interpreted as turbidites.

There is, in addition, another possibly comparable set of sediments, recorded in the literature. Walker (1966) describes a variety of laminated and rippled sand silts and mudstones, this facies occurring within the distal, downslope areas of a Carboniferous delta system. These sediments were thought by Walker to have been deposited from turbidity currents deficient in sediment, perhaps the fine grained tail of a larger, denser, current.

This discussion is given to demonstrate that various sedimentary sequences comparable to those seen in the Traboyack mudstones, have a close spatial relationship with fan-deltas or deltas. Within such a depositional setting such finely bedded sediments, deposited from both turbidity currents and fallout can only have accumulated in an environment away from the major site of coarse clastic deposition on the delta top.

In view of the above considerations it is interesting to speculate as to which of the fan-delta systems recognised to the north of the Stinchar Valley/Fault these mudstones are related to. Williams (1962) considers the Trayboyack Division to be in part equivalent to the Kirkland Formation (as defined herein). Thus the quartzo-feldspathic turbidites of the Darley Formation were felt to be lateral equivalents of the Kirkland Formation Conglomerate Member. Differences in composition,source area, probable direction of derivation and facies as outlined in section 6:2 are thought to preclude this. Instead, the present author prefers a tentative correlation of the Traboyack mudstones with the Kirkland Formation, the reasons being as follows:

(1) Distal facies of the Benan Formation conglomerates are recognized within the Albany Division (Williams (1962) and chapter 5 herein). Comparable facies of gravel bodies stratigraphically higher than the Benan Formation would be expected to outcrop to the north of the Stinchar Valley as a result of transgression and northwards overlap of the Ballantrae Complex. Thus the Kirkland Formation is the only major accumulation of coarse clastic sediment for which no finer, distal equivalents are recognized.

(2) As mentioned in Chapter 2, the Auchensoul Limestone Member exposures on Doularg Hill might in face be best interpreted as part of the Traboyack mudstones, perhaps accumulating on a local palaeohigh, in shallower water than the mudstones.

(3) This unit provides a possible location for the fine grained sediment, mud and silt, that is noticeably absent from the Kirkland Formation sands and gravels. Such sediment may either have entered the marine environment during flood events, or have been removed from the subaerial fan areas by aeolian activity as outlined in Appendix III.

Onefinal point of interest with regard to the Traboyack mudstones, and indeed the Traboyack Division in general, is the absence of both macro-fauna and ichno-fauna. The possible causes of this can only be speculated upon. Factors of importance may be:

(a) The continual deposition of fine grained sediment from suspension. This will reduce the suitability of a given area for colonization by filter-feeding organisms such as brachiopods, especially in the juvenile stages (Rudwick, 1970).

(b) The Traboyack Division sediments were deposited prior to the Nemagraptus gracilis zone eustatic transgression. Legget (1978) suggests that increased shelf areas resulting from this event led to the increased production of organic material and deposition of carbonaceous black shales as ocean floor sediments, where previously radiolarian cherts had accumulated. This lack of organic matter of marine origin in suspension, and also probably in the sediment may be of significance.

(c) In addition to (b) no organic material can have been supplied from a terrestial source, in view of the age of the units.

(d) These sediments were deposited prior to the establishment of a shallow-water carbonate depositional regime and associated marine organic productivity in the immediate vicinity.

6.3 Albany Division

6.3.1 Albany Mudstones and associated coarse, clastic deposits

Thickness: exposed thickness of approximately 600m.

Type section: Albany Burn as shown in Fig. 6:8.

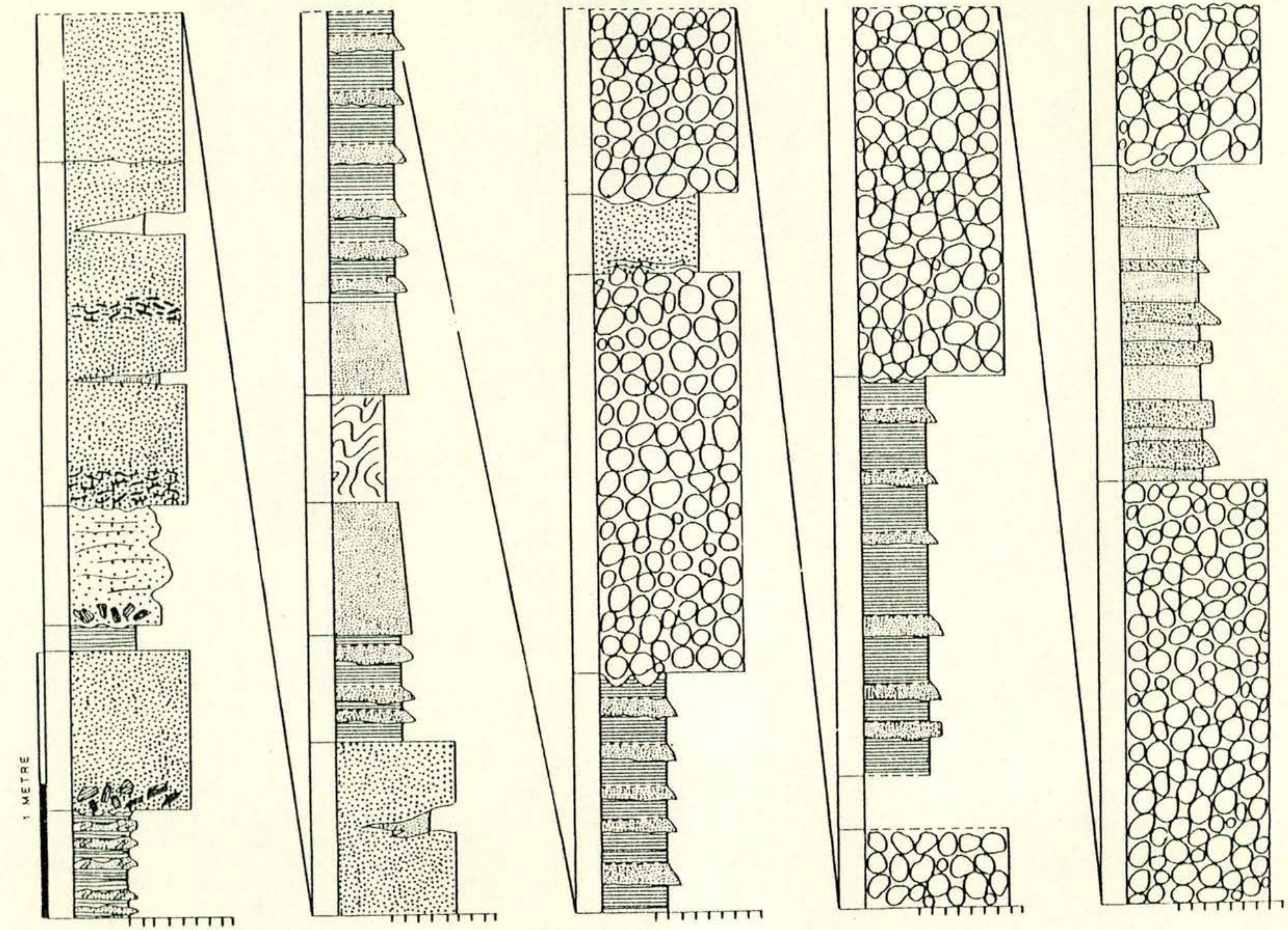
Lithologies: 5 to 10cm thick, parallel-sided, graded, medium sand turbidites lacking C divisions, interbedded with horizontally laminated or more rarely, faintly rippled silty fine sands. The sequence also contains thick-bedded, amalgamated, granule-rich coarse sand turbidites and thick conglomerate units with erosive bases, Fig. 6:8. The Albany Mudstones themselves, from which Tripp (1956) described a trilobite fauna later assumed to belong to the Nileid community of Fortey (1974), (Ingham, 1978) see Fig. 4: 8 , were not located during the present study.

6.3.1a Sedimentology

Figure 6:8 shows a measured section through a sequence of channelized conglomerates and amalgamated sandstones that are erosive into thinly bedded, graded and rippled turbidites and interbedded silty mudstones exposed in Albany Burn. This sequence is strongly reminiscent of the one exposed in the Water of Gregg, near The Stables (Fig. 5) correlated with the Benan Formation Conglomerate Member. As in the Water of Gregg conglomerates those exposed in Albany Burn also contain clasts of Stinchar Limestone

Figure 6.8

MEASURED SECTION THROUGH CHANNELISED CONGLOMERATES ,ALBANY BURN



m s f s m s c s g p c b

LEGEND AS FOR PREVIOUS LOGGED SECTIONS

Formation lithologies. The remainder of Albany Burn sequence is unfortunately inaccessible and has not been logged, but would appear to consist of thin 3-5cm thick, graded fine sand turbidites. It is not possible therefore to say with confidence whether the sequence shown in Fig. 6:8 is related to the sediments outcropping above and below, or whether it is a fault slice, out of stratigraphic sequence.

The Albany Mudstones contain brachiopod and trilobite faunas that allow correlation with the Stinchar Limestone Formation and the Lower part of the Benan Formation (Williams, 1962, Tripp, 1965, Ross and Ingham, 1970 and Ingham, 1978). The trilobite fauna is typical of the Nileid community of Fortey (1975), see section 4.7 indicative of outer shelf water depths. The Albany Mudstones are considered to be lateral equivalents of the upper part of the Stinchar Limestone Formation, that accumulated in a down-slope, deeper water environment.

6.3.2 Craigmalloch Formation

Thickness: approximately 500m.

Type section: Water of Gregg, between The Stables (NX29 2900 9405) and 100m upstream from Lockston (NX29 2820 9415).

Lithologies: Massive, chaotic, cobble and boulder conglomerates, with discrete units of thick bedded, coarse-grained, lithic greywacke turbidites and more thinly bedded, fine sand and silt turbidites (Plate 6:6), (Figs. 6:9 & 6:10). Gravel units are composed for the most part of clasts derived form an ophiolitic terrain, the Ballantrae Complex, although a wide variety of granitoids also occur. Matrix to the conglomerates and sands throughout the rest of the unit is of basic lithic greywacke composition, feldspar content increases and lithic content decreases with decreasing grain size, quartz content is consistently low.

Fauna: A previously unrecorded fauna was collected in 1981 by S.P. Tunnicliff and Dr A.W. Rushton (I.G.S., London) from the fine-grained, hemipelagic tops of medium sand turbidites outcropping the Water of Gregg near Changue House (NX29 2892 9401), consisting of the following:

Scyphozoa

Archaeoconularia sp.

Brachiopods

?Eodinobolus sp.
Sericoidea sp.

Gastropods

Archinacella sp.
indet. flat-spired gastropod

Bivalve

?Myoplusia sp.

Trilobites

?cyclopygid (small
Homalopteon cf. portlockii (Salter)
det. A. Rushton

Phyllocarid

?Ceratiocaris sp. (spines and "jaws" and probably the origin of amorphous black masses on bedding surfaces)

Graptolites

?Aspidograptus sp.
?Callograptus sp.
Dictyonema cf. fluitans Bulman
?Nemagraptus sp.
Clinacograptus cf. caudatus Lapworth
Dicellograptus cf. intortus Lapworth
Dicranograptus nicholsoni minor Bulman
Glyptograptus sp.

S.P. Tunnicliff (pers. comm., 1982) concludes that the presence of Dicellograptus C.F. intortus and Dicranograptus n. minor together with probably Nemagraptus fragments indicates a Nemograptus gracilis zone horizon. In Chapter 2 the stratigraphic position of the N. Gracilis zone was discussed and following Ingham (1978) considered to be for the most part of Llandeilo age. This would indicate that deposition of the Craigmalloch Formation was synchronous with the

Stinchar Limestone Formation, Albany Mudstones and possibly, although it is felt unlikely, the Benan Formation. In this case the Craigmalloch Formation may have belonged to a separate depositional system, to these units.

6.3.2a Sedimentology

Figures 6:9 and 6:10 show measured sections through the formation and allow the recognition of three component facies:

(a) Massive, disorganised, cobble and boulder conglomerates (Plate 6:6, Figs. 1 & 3). Units of this facies are up to 15m in thickness and comprise both matrix and clast supported gravels. In addition, a wide variety of granitic lithologies occur, as do metaquartzites and clasts of pinkish limestone dissimilar to any lithology seen in the Stinchar Limestone Formation. Clasts vary in size from granules as part of the sandy, mud-free matrix, to boulders in excess of 1m. Within the conglomerate units well-defined, non-graded beds of medium to coarse sand and granule conglomerate can be recognized, although sand bodies are generally more lenticular and laterally discontinuous. In addition to these clearly defined sandstone units distorted beds of coarse sand also occur in the conglomerate units (Plate 6:7, Fig. 1). These are thought either to have been deformed during slumping or sliding of a conglomerate mass or alternatively to have been disrupted whilst at the sediment surface during the passage of a gravel laden current. The disorganized, often matrix-supported fabric of these conglomerates indicates that they were deposited from sandy debris flows. The high clast:matrix ratio seen at many horizons suggests that in addition to matrix strength dispersive pressure resulting from clast/clast interactions may also have been important in maintaining the large cobbles and boulders in suspension within the flow during transportation.

(b) Graded turbidite sands, Figs. 6:9 and 6:10. Well-defined graded sandstones 20-40cm thick, with erosive, often gravelly, Plate 6:6, Fig. 2, and loaded bases. No current ripples (Bouma Division C) are seen, although horizontal lamination is fairly common in the upper parts of these beds. The presence only of Bouma divisions A, B and E indicates deposition from relatively fast moving, high density turbidity currents, the erosive and

Figure 6.9

MEASURED SECTION IN STREAM BED WATER OF GREGG, FROM CRAIGMALLOCH DOWNSTREAM

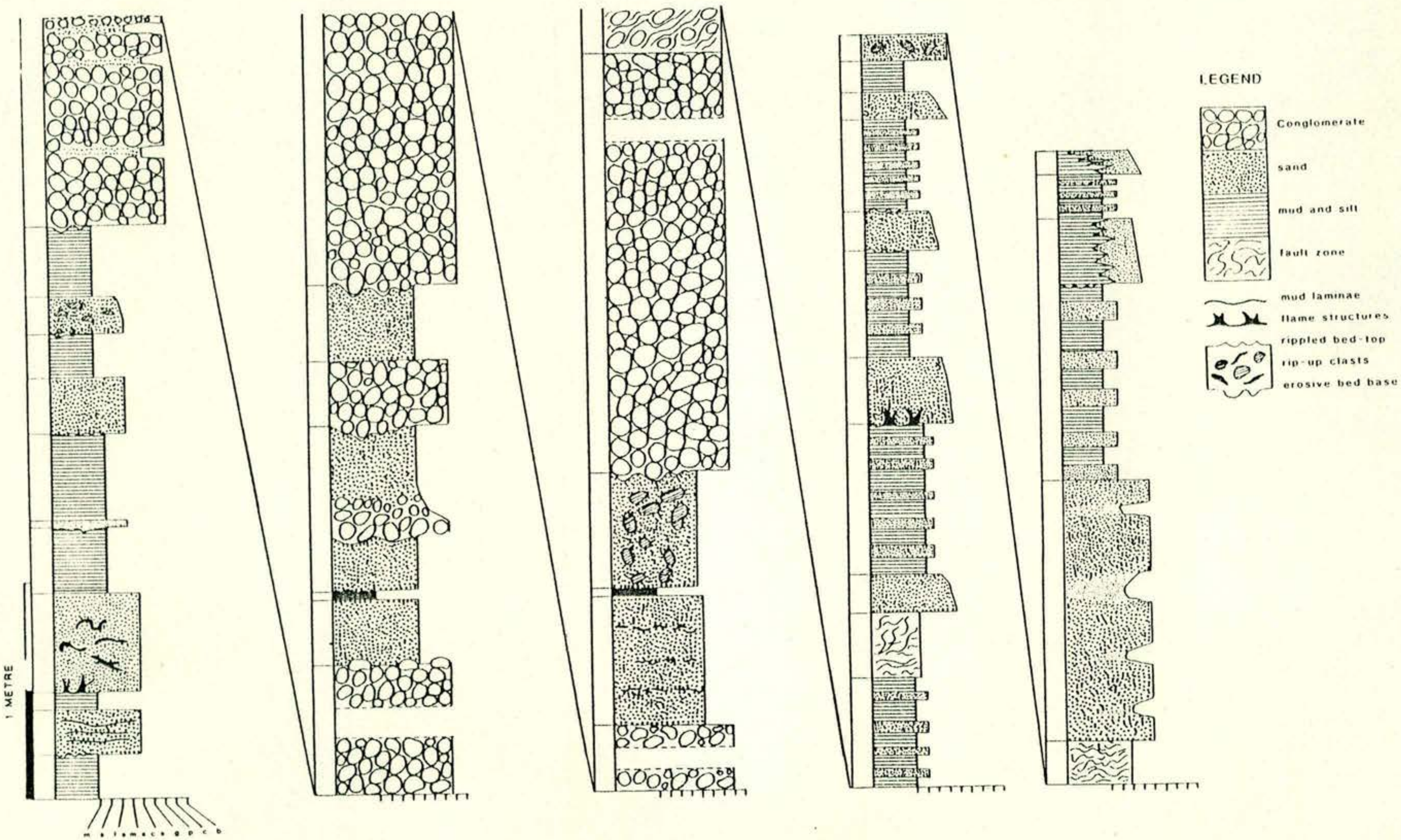


Figure 6.10

MEASURED SECTION WATER OF GREGG CONTINUED FROM PREVIOUS FIG.

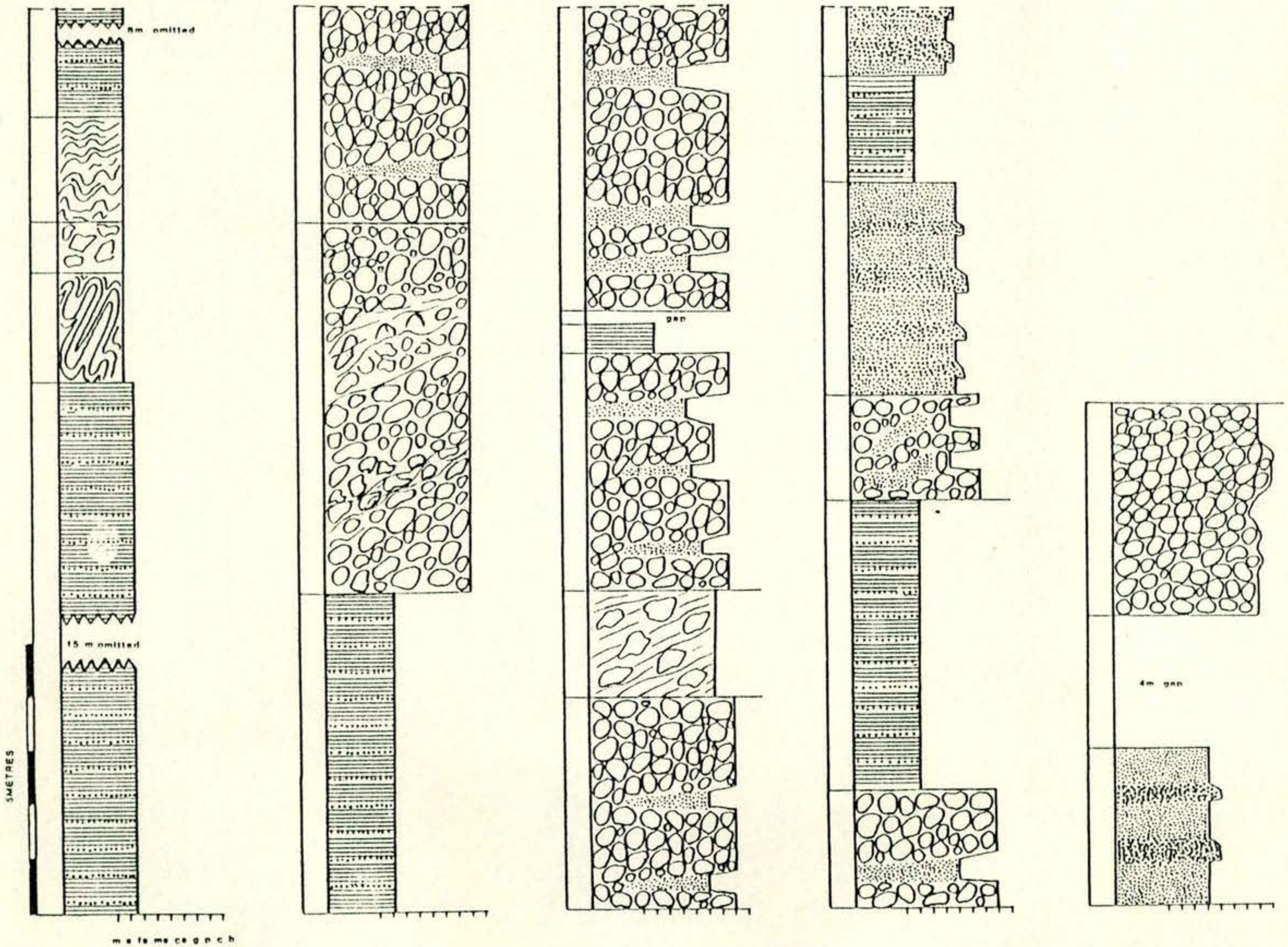


Plate 6.6

Figure 1.

Chaotic, matrix supported, conglomerates and disrupted coarse sand horizons in Craigmalloch Conglomerate Formation. Note also the brittle deformation of the larger clasts.

Locality, Water of Gregg (NX29,287 942).

Scale is given by hammer shaft (30cm).

Figure 2.

Graded, turbiditic, conglomerates and sandstones in the lower part of Craigmalloch Formation, the beds young to the left. The gravel horizons occur as the lowest parts of the individual turbidite units.

Locality, Water of Gregg (NX29,288 941).

Scale is given by metre stick.

Figure 3.

Faulted contact between conglomerates, to the left, and silty, very fine sand thin turbidites, to the right, of the Craigmalloch Conglomerate Formation. The fault is vertical and strikes SW-NE.

Locality, Water of Gregg (NX29,287 942). Exposure approximately 1.75m high at fault.

Plate 6.6

Figure 1

Figure 2

Figure 3

irregular bed bases are also indicative of turbulent flow. In addition to these clearly defined singly bedded units, thicker, amalgamated and massive sandstones interdigitate with the laminated fine sands and muddy silts that form the third major facies in the formation. Units of this type are seen only near the middle of the measured section (Fig. 6:9).

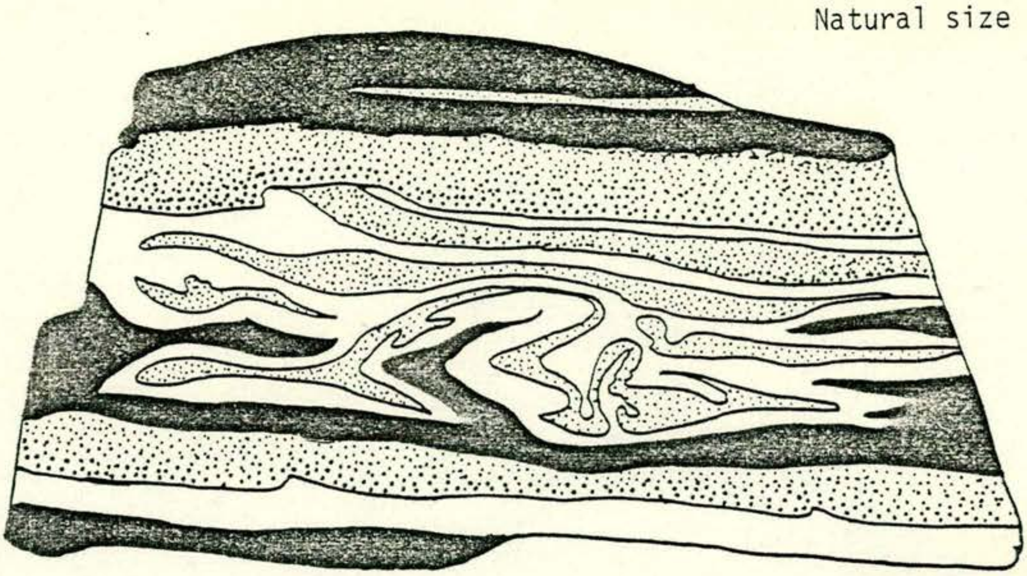
(c) Mudstones and siltstones with laminated and rippled fine to medium sands (Plate 6:6, Fig. 3). These constitute a significant proportion of the Water of Gregg sections, often occurring interbedded with graded, somewhat coarser, discrete, sandy turbidites (Figs. 6:9 & 6:10 and Plate 6:7, Fig. 3). The finely laminated sands and rippled sands are thought to have been deposited from small fine-grained turbidity currents. Deposition from the fine tail of a larger turbidity current is considered unlikely as the passage of such a sediment flow is likely to result in erosion of the underlying sediment. Evidence for this lacking, unless the erosion is associated with an immediately overlying thicker turbidite bed, Plate 6:7, Fig. 3. Small scale slump and contorted structures (Plate 6:7, Figs. 2 & 3 and Fig. 6:11) are moderately common indicating deposition on a slope, although the absence of well-developed slump overfolds precludes their use as palaeoslope indicators.

The association of facies described above is reminiscent of those recorded from coarse grained submarine fan deposits by Walker (1978). In Walker's model for re-sedimented conglomerates found in association with turbidites thick conglomeratic debris-flow units are interpreted as major channel infillings: Minor channel deposits are represented by amalgamated sandstones. The laminated siltstones represent overbank, interchannel deposits, the thick well-defined turbidites are interpreted as non-channelized depositional lobe deposits. Unfortunately the limited extent of the Water of Gregg exposure prevents the recognition of any channel-fill bodies.

A further factor that may be of importance is the occurrence above the top of the formation, in the stream bed by Lockston (NX29 2820 9415) of a thin limestone unit correlated by Williams (1962) with the Stinchar Limestone Formation. If these exposures

Sketches of small scale slumps in Craigmalloch Formation.

Natural size



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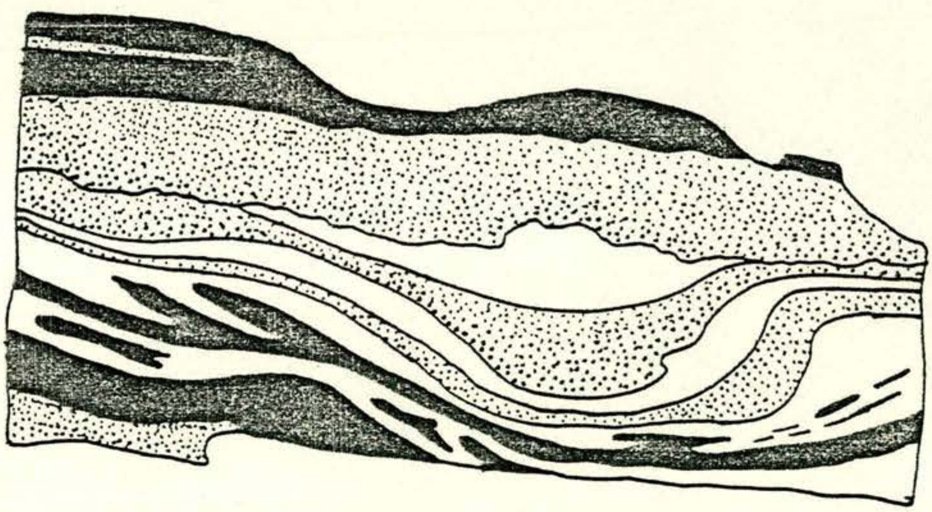

GW1480B

Plate 6.7

Figure 1.

Massive, chaotic, matrix supported conglomerates and thick, graded, coarse sand turbidites, in Craigmalloch Conglomerate Formation. Locality, Water of Gregg (NX29,287 942). Outcrop is 1.75 - 2.00 metres in height.

Figure 2.

Detail showing erosion and loading at base of thin sand turbidite in finer grained section of Craigmalloch Conglomerate Formation.
Locality, Water of Gregg (NX29,287 942).
Scale is given by pen (13cm).

Figure 3.

Detail showing small scale slump horizon overlain by erosively based, graded and faintly rippled fine to medium sand turbidite, Craigmalloch Conglomerate Formation.
Locality, Water of Gregg (NX29,287 942).
Scale is given by tape measure (5.5cm).

Plate 6.7

Figure 1

Figure 2

Figure 3

are in their correct stratigraphic position and have not been tectonically juxtaposed against the Craigmalloch Formation, a possibility that cannot be eliminated, the limestones with their shallow-marine fauna may indicate that the conglomerates and associated sediments also accumulated in comparatively shallow water.

In view of this it is felt that an analogy for the Craigmalloch Formation may be found in the Lower Miocene Kemer Formation of theKemer region, S.W. Turkey. These sediments are described by Hayward (1982) and interpreted by him as representing part of the relatively shallow water submarine 'toe' to a fan-delta complex. Thick massive, debris flow conglomerates thought to have been deposited in proximal submarine channels are strongly erosive into thinly bedded sandstones and interbedded mudsontes. Other interchannel sediments consist of graded and structureless amalgamated turbidite sands that form depositional lobes.

If this interpretation is correct then one would expect to find the subaerial regions of this fan somewhere to the north of the Stinchar fault, perhaps in the area around the Mull of Miljoan (NX29 2775 9650) and Milton Hill (NX29 2990 9695) in areas previously mapped as Benan Conglomerate, Geological Survey, Sheet 8, Carrick. The age indicated by the graptolite fauna recovered by S.P. Tunnicliff, see section 6.3.2, indicates that the Craigmalloch formation may have been deposited at approximately the same time as the Stinchar Limestone Formation. This may suggest that rather than ceasing altogether after the abandonment of the Kirkland Formation fan-delta, coarse-clastic deposition merely shifted to a new location. Lateral shifting of the locus of deposition is common place in alluvial-fan deposits (Heward, 1978) and results from capture or diversion of the sediment supplying stream, in the source area.

6.4 Summary and discussion

Sedimentological interpretation of the various stratigraphic units found within part of the area bounded to the N. and S. by the Stinchar and Glen App faults indicates that a variety of depositional environments are present.

Ocean floor and trench sediments are thought to be represented by the Darley Formation. The general lack of lithic or mineral grains indicative of derivation from the Ballantrae Complex, a north-easterly derivation and the tectonic nature of both upper and lower contacts of the unit indicate that the Darley formation is genetically unrelated to the rest of the sequence. The distinctive composition and slope parallel palaeocurrents suggests that these turbidite sands were transported longitudinally within the presumed trench, having entered this system from a separate source area via a source further along the margin, to the north-east.

Along the lower boundary of the unit, the Glen App fault, lenses of chert and pillow lavas, of oceanic affinity (Legget, 1979, Lambert et al., 1981) are thought to represent offscraped slivers of the uppermost oceanic crust. Comparable units, consisting of pillow lavas, cherts and/or black shales are found throughout the Northern Belt of the Southern Uplands along major strike faults that denote the bases of thick stratigraphic units tectonically emplaced within an accretionary prism (McKerrow et al., 1977, Legget, 1979, 1980, Legget et al., 1979[a], 1979[b], 1982). The upper boundary of the Darley formation is again tectonic and juxtaposes the quartzo-feldspathic turbidite sands of this unit, against and below the lithic Changue formation. The junction itself consists of a zone of admixed sediments, with small-scale folds also present. The top part of the Darley formation sequence is also folded, into a relatively large near vertical, tight, near isoclinal syncline. Both folding and the formation of the disturbed, admixed zone are thought to have formed as a result of the underthrusting process. Fold styles relative to the contact are thought to reflect deformation as a result of 'drag' along the plane.

The overlying Changue Formation is thought to have been deposited in a lower slope or base of slope environment. The bodies of massive, generally structureless sand found in this unit conform with the usages of the term fluxo-turbidite recommended by Stanley and Unrug (1972), given that the steep bedding precludes recognition of any 'shoe-string' channel morphology. Fluxoturbidites are generally thought to have been deposited in submarine channels (Stanley, 1961, 1967, Stanley and Bouma, 1964, Stanley and Unrug, 1972, Stanley et al., 1978), either on the continental slope, or in the proximal reaches of the base of slope fans that form the continental rise (Rona, 1969).

Outer shelf and possibly upper slope deposits, consisting largely of sediments interpreted as the distal facies of fan deltas are thought to be represented in the Traboyack and Albany Mudstones and the Craigmalloch Formation.

Deformation, occurring both penecontemporaneously, during the development of the accretionary prism, and during the final closure and suturing of Iapetus, during the Silurian/Devonian, would be responsible for the eventual juxtaposition of sediments deposited in differing environments within the continental margin.

Whilst there are certain problems inherent in this interpretation,it is felt that, provided the sedimentological interpretations are correct, weaknesses inherent in the accretionary wedge model proposed by Legget et al. (1979) may hereby be resolved.

Accretionary wedge models so far developed fail to account for the earliest, Llanvirn to Llandeilo, evolution of the margin after the emplacement of the ophiolitic Ballantrae Igneous complex. Furthermore the supposed juxtaposition, across the Stinchar Valley, of sediments deposited in a shelf environment, the Barr Group (this thesis) and sediments supposedly deposited at depths of perhaps 5Km in an ocean trench, and representing the oldest accreted sedimentary slice in the Southern Uplands Legget, without any slope sediments present is one of the major problems in the accretionary prism model proposed by McKerrow et al. (1977) and developed in a series of papers by Legget (1979, 1980) and Legget et al. (1979[a], 1979[b], 1980, 1982).

The lower slope is often a site of major sediment accumulation at the present day (Stanley and Unrung, 1972), and therefore may possess a high preservation potential, as a geomorphic unit. In addition to this somewhat theoretical query, the presence within the Stinchar to Glen App area of algal carbonates (Auchensoul

Limestone Formation of Doularg) and trilobite faunas indicative of outer shelf water depths (Albany Mudstones) is thought to refute the supposed oceanic trench affinity of all sediments in this tract of land.

CHAPTER 7

SUMMARY AND DISCUSSION

7.1 Summary

The immediate conclusions already presented at the ends of Chapters 3, 4, 5 and 6 will be restated and expanded upon so as to provide a concise account of the facies present in the Barr and Tappins Groups. Changes through time in the depositional environments present in the area are related to eustatic and local tectonic events.

The lowest exposed unit in the Middle Ordovician Barr Group sedimentary sequence that overlies the Ballantrae Igneous Complex is the Conglomerate Member of the Kirkland Formation. The gravels that constitute the major part of the Member display fabrics that may be indicative of deposition from sub-aerial sheet floods. Alternatively deposition may have occurred due to the rapid deceleration of a coarse grained effluent flood on entering a standing body of water. In view of this and because the overlying clastic and carbonate units are of shallow water origin, deposition of the Conglomerate Member is thought to have taken place in a fan delta setting. Fan deltas, coastal alluvial, fans and subaerial alluvial fans, both as present day geomorphological features and as sediment accumulations preserved in the geological record, usually display an intimate association with faults (Heward, 1978 p.679, and references therein). Such faults are the agents responsible for the juxtaposition of a high relief terrain against an area of lower ground where sediment may accumulate, a prime requisite for fan formation (Denny, 1965 p.63). In the case of the Conglomerate Member fan-delta it is not possible to conclusively locate a fault. However, (as no Kirkland Formation sediments are found tothe north of the Water of Assel) it may be suggested that it was against one of the major faults in this valley that the Kirkland Formation sediments accumulated. The thickness of the Conglomerate Member, in excess of 250m is such that synsedimentary activity on this inferred fault must have taken place. Those fans that develop along a fault scarp without any movement taking place along that line are only minor and relatively thin accumulations (Heward, 1978 p.690, Denny, 1965 p.58) as no maintenance of source area topography occurs, to provide a continued supply of sediment.

Exposure of the Ballantrae Igneous Complex took place during the middle or late Arenig, as proposed by Bluck,(1978)and Ingham, (1978) the apparent age problem posed by the previously reported Llahdeilo age for cherts associated with pillow lavas exposed in the Craighead Inlier (Lamont and Lindstrom, 1957) is resolved in Appendix IV. Prior to the upper Arenig the Ballantrae Igneous Complex was the site of chert and black shale deposition (Bluck, 1978, Stone & Strachan, 1981) with sediments derived from basaltic lavas (Bluck, 1982) with sedimentary melanges (Bluck, 1978) also present. Whilst the lava derived sediments may well have been deposited in shallow water conditions (Bluck, 1982) there cannot have been a major non-ophiolitic sediment source available in the area until the Llanvirn. The possible mechanisms by which exposure of the Complex may have been brought about have already been outlined in Chapter 1, and will not be reiterated here.

The newly uplifted Ballantrae Complex provided a source for the basaltic, gabbroic and chert clasts that constitute the vast bulk of the Conglomerate Member. In addition large boulders (1m) of alkali feldspar syenite and trachytic lavas indicate that a non-ophiolitic terrain was also exposed in close proximity to the eventual site of sediment accumulation.

The Conglomerate Member becomes somewhat less coarse grained towards the top of the unit and finally passes upwards into the Transitional Sandstone Member, a fan-delta top distributary system, with interdistributary bay or coastal lagoon sediments represented by the laterally equivalent Auchensoul Limestone Member. Subsidence and/or transgression of the fan-delta top gave rise to the non-channelized shallow-marine sands of the Benan Burn Sandstone Member, as a result of inferred shoreline retreat and concomitant facies shift. These shallow-marine sands become less coarse upwards and, eventually, clastic input decreased sufficiently to allow a sedimentary regime dominated by local production and deposition of carbonates, the Stinchar Limestone Formation, to become established.

The Kirkland Formation sediments are therefore thought to document the gradual abandonment of a fan delta. The reduction in sediment supply may relate to reduction in source area relief and/or diversion of the sediment supplying stream as a result of either tectonic or alluvial processes in the hinterland as outlined by Heward (1978).

The Stinchar Limestone Formation is interpreted as an assemblage of shallow-subtidal carbonate facies, closely comparable to those found in present day areas of warm water shallow marine carbonate deposition. Periodic storm events are inferred from the presence of sub-littoral sheet-sandstones and intraclast conglomerates within the Stinchar Valley Member and oncolitic lag horizons within the lagoonal facies of the Tormitchell Member. Shallow marine conditions persisted during the deposition of the Formation and there is no evidence for the extensive subsidence seen in the Kirkland Formation, although transgression and overstep of the Ballantrae Complex basement may have occurred, north of the Water of Assel.

Carbonate deposition was brought to an abrupt close by a rapid increase in water depths, from shallow subtidal to outer shelf conditions. Synsedimentary fault activity took place along a line furthere north than the Water of Assel. This, combined with the effects of the Nemagraptus gracilis zone eustatic transgression was responsible for the rapid facies change. At the same time source area uplift resulted in the influx of vast quantities of coarse gravels of the Benan Formation onto the foundered platform/shelf area. One factor that could have caused the period of rapid uplift is the intrusion of granite bodies into a hinterland that had previously been of relatively low relief. The presence of granite clasts yielding an isotopic age of 459$\pm$ 10my (Rb/Sr) allows sufficient time for the uplift and erosion of these granite bodies prior to the eventual deposition of this detritus in sediments of upper Llandielo/Lower Caradoc age. Longman et al. (1979) propose that intrusion of these bodies took place within a magmatic arc situated immediately to the north of the Girvan region. Northerly subduction and subsequent melting of oceanic crust was invoked as a means of generating these magmas. As outlined in Chapters 1 and 6 this situation is unrealistically small-scale. Comparison with present day arc-trench systems shows that the gap between these two features is in the order of 55-100km. To reconcile this disparity three alternatives are considered.

(i) The granites, if intruded in the vicinity of Girvan, were not related in terms of their genesis to any subduction process.

(ii) The river/stream system in which this detritus was transported was far more extensive in a northerly direction, than has previously been assumed.

(iii) The subduction zone to which the proposed magmatic arc was related lay much further to the south than the Southern Uplands Fault, considered by all previous authors to be the most likely location for this feature. Whilst there may be a case for suggesting that the S.U.F. does not necessarily, as a present day physiographic feature relate to an ancient plate boundary, it would be naive, in the light of the accepted accretionary wedge interpretation of the Southern Uplands, to suggest that any trench/subduction zone lay sufficiently far south to allow the presence of an arc terrain along the southern margin of the Midland Valley.

Lower horizons of the Benan Formation conglomerates exposed along the Stinchar Valley are thought to have been resedimented from the shallow water areas of a coastal alluvial fan by a variety of mass flow mechanisms. These resedimented gravels are laterally equivalent to and interdigitate with, the sporadically developed Mudstone Member (formerly superstes mudstones). These markedly finer grained sediments are thought to have been deposited in areas in between large scale gravel lobes in the submarine to the inferred coastal fan.

Deposition of shallow marine and subaerial deposits, seen at higher horizons within the conglomerates exposed along the Stinchar Valley is thought to have been brought about by fan progradation. This resulted from a decline in subsidence rate whilst sediment input remained at a more or less constant level. This may have allowed the development of a fan-delta from what may formerly have been a coastal alluvial fan.

To the south of the Stinchar Valley/fault complex the sediments of the Tappins Group are for the most part turbidites, of varying compositions. The quartzo-feldspathic turbidites of the Darley Formation appear to have been tectonically emplaced beneath the 'ophiolite-derived' turbidites of the Changue Formation. This may suggest that the Darley Formation sediments were deposited within an ocean trench, as it is in this location that subduction related accretion of sediment 'packets' beneath the continental margin takes place (Karig and Sharman, 1975, Dickinson and Seeley, 1979).

The remainder of the Tappins Group is thought to have been deposited in outer shelf and upper slope environments as outlined in Chapter 6. If this interpretation is correct then together, the Barr and Tappins Groups display, albeit scantily, a transition from shallow shelf and subaerial environments to ocean trench conditions. And thus may represent a continental margin sequence deposited for the most part, before sediment accretion gave rise to the Southern Uplands wedge.

7.2 Implications of the Barr Group sediments for the Northern Margin of Iapetus

In recent years with the development of plate-tectonic theory and the documentation of present day depositional sedimentary environments it has become apparent that certain sedimentation patterns and sediment types may typify a particular tectonic environment or process (Burke and Drake, 1974, Mitchell and Reading, 1978).

Plate boundaries and continental margins in particular have been the subject of much interest and three broad types are recognized each characterized by a particular type of tectonic process and relative plate motion.

(i) Divergent boundaries (rifted or passive margins) where two plates are moving apart as a result of the addition of new lithosphere either at a mid-ocean ridge (intercontinental rift) or in the median valley of an intra-continental rift such as the East African Rift. Intra-continental rifts will contain fluvial and lacustrine sediments, in accumulations perhaps 3-5km thick as in the Baikal Rift. Intercontinental rifts may develop from an intracontinental one provided sufficient new, oceanic-type crust is added in the axial zone. In the early stages of the development of inter-continental rifts, tectonism may be manifested in the form of subsidence along major normal faults at the rift margins, with rotation of the blocks defined by these faults. Marine incursion as a result of subsidence of the central portions of the rift may result in evaporite precipitation, as in the Red Sea (Hutchison and Engels, 1970)and the North Sea (Taylor and Colter, 1975). Nonmarine sediments (alluvial fans, talus cones and other alluvium) may occur on the rift flanks, possibly inderdigitating with lavas erupted along fissures. As rift evolves it may become a major site of sediment deposition, for example the North Sea, and the Jurassic of East Greenland, where normal faulting and associated subsidence still provided the major control over sedimentation (Anderton et al., 1979, Surlyk, 1978, Hallam and Selwood, 1976).

In the later stages of their development rifted margins evolve into major sites of sediment accumulation (Sheridan, 1974) with well defined shelf, slope (and canyon) base of slope and basin plain environments.

(ii) Destructive (or convergent) plate boundaries occur where oceanic crust plunges beneath a continental mass. The resultant crustal downwarp (subduction zone) is generally equated with the site of a major deep sea trench. Associated with the subduction zone/trench and separated from it by an arc-trench gap of 50-400km, a volcanic (or magmatic) arc occurs within the overriding plate, with magmas forming as a result of melting of the descending plate. In the arc-trench gap an accretionary prism may develop (provided sedimentation rates are high enough) as a result of the subduction process (Karig and Sharman, 1975) and additionally a complex assemblage of sedimentary basins may form within this setting (Dickinson and Seely, 1979, Underwood and Backman, 1982). Sedimentation within the arc itself is dominated by deposition of pyroclastic rocks and lava-derived sediments. Behind the magmatic arc, a back-arc (or retro-arc) basin may develop, as a result of rifting and perhaps back-arc spreading (Karig, 1970). Such marginal basins may be the site of major sediment accumulations, and are in many ways similar to the earlier developmental stages of a rifted margin. In summary, convergent margins may be typified by volcanic activity resulting from plate destruction. Subduction may result in the underthrusting and offscraping of sediments deposited in oceanic and trench areas, leading to the development of an accretionary complex.

(iii) The third type of continental margin, transform or strike slip, is typified by a relative lateral motion of the two plates. The types of tectonic processes operative along such margins (transpression and transtention have already been described (Section 1.3.4).

The purpose of this resume of the differing kinds of processes and sediment occurring at different types of continental margin has been to provide a background within which to assess the Barr Group, and thus to comment upon the type of processes that may have operated along the northern margins of Iapetus. Such comments must, however, be made with caution as there may be a considerable overlap between the continental margin types outlined above in terms of the sedimentary and tectonic processes operative at any one point in time and space. In order to correctly determine the significance of the Barr Group sediments in the context of the continental margin upon which they were deposited it is felt necessary to identify certain features of the Scottish Caledonides, as below.

The Southern Uplands as a whole has been interpreted as an accretionary prism, consisting of sediments deposited within an ocean trench northwards (Piper, 1972, Mitchell and McKerrow, 1975, McKerrow et al., 1977, Legget et al., 1979, 1982). This would indicate the existence of a destructive plate boundary in the southern Scottish area.

Palaeomagnetic evidence indicates a considerable lateral separation of the Scottish and Anglo-Welsh areas during the Lower Palaeozoic (Scotese et al., 1979, Kent and Opdike, 1978). These authors propose strike-slip motion during the Carboniferous as the mechanism by which these two areas were brought together, although Dewey (1982) suggested that motions of this type may have occurred from the early or middle Ordovician.

There are various features of the Barr Group that are felt to be important in determining which the the sets of processes listed above were most likely to have influenced sedimentation.

(a) Sedimentation during the Llanvirn, Llandeilo and ?Lower Caradoc (the stratigraphic duration of the Barr Group) was controlled by a series of normal faults downthrowing to the S. The extent of subsidence along these faults is considerable, at least 750m in the case of that associated with the Benan Formation.

(b) Subsidence and sedimentation rates cannot be accurately determined as neither graptolite nor conodont faunas are sufficiently abundant to allow the establishment of a clearly defined biostratigraphy that an be equated with published absolute time scales. It is however possible to establish that deposition of the Benan Formation took place in a period of 3-5 million years, from the upper Llandeilo to Lower Caradoc, using the time scale proposed by Churkin et al. (1977). This would give a sedimentation rate of 160m to 250m per million years. Subsidence rates may be assumed to be the same on average, although were probably more rapid at the onset of Benan Formation sedimentation, resulting in the very brief passage from the Stinchar Limestone Formation.

(c) At the same time as rapid subsidence of basinal areas was taking place, uplift of potential source areas must have taken place to maintain the supply of coarse grained sediment during deposition of the conglomeratic Members of the Group.

(d) The width of the shelf upon which the Barr Group was deposited is thought to have been very narrow. This is indicated by the preservation in the Transitional Sandstone Member of primary sedimentary structures thought to have been produced by fluvial processes operating in a fan-delta top distributary system. Low tidal ranges on present day situations show a positive correlation with a narrow shelf width (Cram, 1979). This observation is supported by the restricted distribution of the shallow water facies of the Barr Group.

(e) In general terms deposition of the remainder of the Ordovician sequence of the Girvan region is thought to have been controlled by a similar type of fault activity to that which determined the distribution of Barr Group sediments, and finally attained a thickness of approximately 5km (Williams, 1962).

Rapid subsidence of sediment receiving areas, with simultaneous uplift of source terrains, the accumulation of thick clastic sequences whose distribution is controlled by syn-sedimentary faulting and narrow shelf widths with concommitant rapid lateral facies shifts are together thought to indicate a transtensional strike or oblique slip regime (Mitchell and Reading, 1978, Reading, 1980, Link and Osborne, 1978, Steel and Gloppen, 1980). A rifted or passive margin setting can be ruled out as northwards subduction beneath the Midland Valley is thought to have taken place at the same time as the Barr Group was being deposited (Legget et al., 1982, Dewey, 1982, Yardley et al., 1982). Given this then oblique subduction of part of the Iapetus oceanic crust would allow both localized transtensional tectonics in the Girvan region and convergent transpressional tectonics in the Southern Uplands. This latter led to the development of an accretionary prism. Oblique subduction below the Midland Valley has been postulated by Philips et al., (1976) and Dewey, (1982) during the Caradoc but evidence for this type of activity during the Llanvirn-Llandeilo has previously been lacking.

The possibility that the Tappin Group contains sediments deposited in shelf and slope environments is thought to refute the suggestion of Legget et al., (1979 and 1982) that this unit is truly part of the Southern Uplands accretionary Complex. Rather than detract from an accretionary wedge model for the Southern Uplands, the author feels that recognition of a possible slope sequence strengthens it in that it may not be necessary to invoke strike-slip removal or subduction of all Llanvirn-Llendielo sediments as proposed by Legget et al. (1982).

The location of the line along which any strike-slip motion and subduction south of the Midland Valley took place is assumed to be the Southern Uplands fault (Dewey, 1969, 1971, 1982, Mitchell and McKerrow, 1976). In the Girvan/Ballantrae area the location of this major fault line, previously thought to be locally represented by the Glen App Fault has been called into question by McKerrow et al. (1977) who suggest that the continuation of the Southern Uplands Fault may in fact be the Stinchar fault. Furthermore, Legget et al. (1982, p.515) suggest that as clast lithologies in the Corsewall conglomerate (Llandeilo-Caradoc) of Corsewall Point, Rhinns of

Galloway can be matched with lithologies in the Ballantrae Igneous Complex. If this is so than no strike-slip motion can have taken place along the Southern Uplands Fault, which they equate with the Stinchar Fault.

As stated above, it is thought that Barr Group sediments were deposited in a tectonic setting resulting from oblique-slip motion. Moreover, within the area studied it is also possible to correlate across the Stinchar Fault. This suggests that the site of a middle Ordovician oblique-slip/subduction must be most readily equatable with the Glen App and not the Stinchar Fault. To test the validity of this opinion, one might try to trace clast lithologies typical of the Ballantrae Complex, or any other identifiable source within the Midland Valley, in the Southern Uplands proper.

7.3 Further work

In the author's opinion, there are various worthwhile lines which future research might follow in order to shed further light on the geological evolution of the Girvan region, the Southern Uplands and Scottish Caledonides as a whole.

Firstly, the remainder of the Ordovician sequence in the Girvan region needs to be investigated with the same aims as the present work. This would establish whether the same control over sedimentation as are thought to have been active during depsotion of the Barr Group continued to be operative. At the same time the facies and environments present in one of the best known sedimentary sequences in the British Isles would at last become fully understood. In particular the Benan Formation conglomerates are thought to be worthy of attention, not only as part of the Girvan sequence, but also potentially as a fan-delta-coastal alluvial-fan complex, of which there are relatively few documented in the geological record.

Within the Southern Uplands proper, there is still a great need for detailed structural and sedimentological studies, these to be used to test and improve upon the current accretionary wedge models. In particular it would seem desirable to document the nature and orientation of the stresses that produced folds or other small-scale structures throughout the Southern Uplands. The most pressing problem, in the Southern Uplands is, however, the establishment of a more detailed accurate and readily useable biostratigraphy, using perhaps conodonts or acritarchs. This advance must be made before any really worthwhile sedimentological work can be carried out.

On a larger scale still it is the authors opinion that the understanding of Caledonide/Appalachian geology as a whole might benefit from a comparison with the Western Cordillera of N. America. This complex and long lived continental margin has already been employed as a possible analogy by Dewey (1982). In particular the possibility that 'displaced' terrains may move considerable distances along the continental margin before becoming involved in any collision (Nur and Ben-Avraham, 1978) and may undergo considerable rotation, resulting in abrupt changes in structural style at block margins (Beck, 1980) are thought to be worth bearing in mind when looking at the Caledonides.